

PATENT APPLICATION
REPOSITIONING AND REORIENTATION OF MASTER/SLAVE
RELATIONSHIP IN MINIMALLY INVASIVE TELESURGERY

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REPOSITIONING AND REORIENTATION OF MASTER/SLAVE RELATIONSHIP IN MINIMALLY INVASIVE TELESURGERY

CROSS-REFERENCES TO RELATED APPLICATIONS

The present application is a divisional of and claims the benefit of priority
5 from Application Serial No. 09/398,960 filed September 17, 1999, which is a
continuation-in-part of Application Serial No. 09/374,643, filed August 16, 1999 for a
“*Cooperative Minimally Invasive Telesurgical System*,” and also claims the benefit of
priority from Provisional Application Serial No. 60/116,891, filed January 22, 1999, for
“*Dynamic Association of Master and Slave in a Minimally Invasive Telesurgical System*,”
10 Provisional Application Serial No. 60/116,842, filed January 22, 1999, for “*Repositioning
and Reorientation of Master/Slave Relationship in Minimally Invasive Telesurgery*,” and
Provisional Application Serial No. 60/109,359, filed November 20, 1998, for “*Apparatus
and Method for Tracking and Controlling Cardiac Motion During Cardiac Surgery
Without Cardioplegia*,” the full disclosures of which are incorporated herein by reference.

BACKGROUND OF THE INVENTION

15 The present application is generally directed to medical devices, systems,
and methods. In a particular embodiment, the invention provides telesurgical robotic
systems and methods that flexibly and selectably couple input devices to robotic
manipulator arms during surgery.

20 Advances in minimally invasive surgical technology could dramatically
increase the number of surgeries performed in a minimally invasive manner. Minimally
invasive medical techniques are aimed at reducing the amount of extraneous tissue that is
damaged during diagnostic or surgical procedures, thereby reducing patient recovery
time, discomfort, and deleterious side effects. The average length of a hospital stay for a
25 standard surgery may also be shortened significantly using minimally invasive surgical
techniques. Thus, an increased adoption of minimally invasive techniques could save
millions of hospital days, and millions of dollars annually in hospital residency costs
alone. Patient recovery times, patient discomfort, surgical side effects, and time away
from work may also be reduced with minimally invasive surgery.

30 The most common form of minimally invasive surgery may be endoscopy.
Probably the most common form of endoscopy is laparoscopy, which is minimally
invasive inspection and surgery inside the abdominal cavity. In standard laparoscopic

surgery, a patient's abdomen is insufflated with gas, and cannula sleeves are passed through small (approximately 1/2 inch or less) incisions to provide entry ports for laparoscopic surgical instruments. The laparoscopic surgical instruments generally include a laparoscope (for viewing the surgical field) and working tools. The working tools are similar to those used in conventional (open) surgery, except that the working end or end effector of each tool is separated from its handle by an extension tube. As used herein, the term "end effector" means the actual working part of the surgical instrument and can include clamps, graspers, scissors, staplers, image capture lenses, and needle holders, for example. To perform surgical procedures, the surgeon passes these working tools or instruments through the cannula sleeves to an internal surgical site and manipulates them from outside the abdomen. The surgeon monitors the procedure by means of a monitor that displays an image of the surgical site taken from the laparoscope. Similar endoscopic techniques are employed in, e.g., arthroscopy, retroperitoneoscopy, pelviscopy, nephroscopy, cystoscopy, cisternoscopy, sinoscopy, hysteroscopy, urethroscopy, and the like.

There are many disadvantages relating to current minimally invasive surgical (MIS) technology. For example, existing MIS instruments deny the surgeon the flexibility of tool placement found in open surgery. Most current laparoscopic tools have rigid shafts, so that it can be difficult to approach the worksite through the small incision. Additionally, the length and construction of many endoscopic instruments reduces the surgeon's ability to feel forces exerted by tissues and organs on the end effector of the associated tool. The lack of dexterity and sensitivity of endoscopic tools is a major impediment to the expansion of minimally invasive surgery.

Minimally invasive telesurgical robotic systems are being developed to increase a surgeon's dexterity when working within an internal surgical site, as well as to allow a surgeon to operate on a patient from a remote location. In a telesurgery system, the surgeon is often provided with an image of the surgical site at a computer workstation. While viewing a three-dimensional image of the surgical site on a suitable viewer or display, the surgeon performs the surgical procedures on the patient by manipulating master input or control devices of the workstation. The master controls the motion of a servomechanically operated surgical instrument. During the surgical procedure, the telesurgical system can provide mechanical actuation and control of a variety of surgical instruments or tools having end effectors such as, e.g., tissue graspers, needle drivers, or the like, that perform various functions for the surgeon, e.g., holding or driving a needle,

grasping a blood vessel, or dissecting tissue, or the like, in response to manipulation of the master control devices.

While the proposed robotic surgery systems offer significant potential to increase the number of procedures that can be performed in a minimally invasive manner, still further improvements are desirable. In particular, previous proposals for robotic surgery often emphasize direct replacement of the mechanical connection between the handles and end effectors of known minimally invasive surgical tools with a robotic servomechanism. Work in connection with the present invention suggests that integration of robotic capabilities into the operating theater can benefit from significant changes to this one-to-one replacement model. Realization of the full potential of robotically assisted surgery may instead benefit from significant revisions to the interactions and roles of team members, as compared to the roles performed by surgical team members during open and known minimally invasive surgical procedures.

In light of the above, it would be beneficial to provide improved robotic surgical devices, systems, and methods for performing robotic surgery. It would be beneficial if these improved techniques enhanced the overall capabilities of telesurgery by recognizing, accommodating, and facilitating the new roles that may be performed by the team members of a robotic surgical team. It would further be beneficial if these improvements facilitated complex robotic surgeries such as coronary artery bypass grafting, particularly while minimizing the total number of personnel (and hence the expense) involved in these robotic procedures. It would be best if these benefits could be provided while enhancing the overall control over the surgical instruments and safety of the surgical procedure, while avoiding excessive complexity and redundancy in the robotic system. Some or all of these advantages are provided by the invention described hereinbelow.

SUMMARY OF THE INVENTION

The present invention generally provides devices, systems, and methods which allow one or more of the components of a telesurgical robotic system to be selectively and independently repositioned. Generally, such telesurgical systems include a master controller having an input device which can be operatively associated with an articulated robotic manipulator arm supporting a surgical end effector in a master/slave system so that movement of the input device causes corresponding movement of the end effector. To allow independent movement of the input device or end effector in at least

one degree of freedom, the surgeon will often activate an input device altering the mode of operation of the master/slave control system. In some embodiments, the control system will allow independent repositioning in at least one degree of freedom while inhibiting independent repositioning in at least one degree of freedom. For example, this
5 allows an input handle of the master controller to be translationally repositioned relative to an image of the end effector shown on a display at the master controller workstation, while inhibiting rotational repositioning of the handle relative to the end effector. In other embodiments, a manipulator supporting a surgical instrument such as an endoscope or a tool for treating tissue may be manually repositioned independently of the input
10 handle by actuating an input device on the manipulator, greatly facilitating both set-up and adjustment of the robotic surgical system during a surgical procedure.

In a first aspect, the invention provides a robotic surgical system comprising a master controller with an input handle moveable in a plurality of degrees of freedom. A robotic manipulator assembly includes a surgical end effector which is also
15 moveable in a plurality of degrees of freedom. The control system couples the master controller to the manipulator assembly. A control system has first and second modes. The control system in the first mode is configured to effect corresponding movement of the end effector in response to movement of the handle. The control system is configured to allow independent repositioning of the handle or the end effector in at least one of the
20 degrees of freedom, and to inhibit independent repositioning in at least one of the degrees of freedom when the control system is in the second mode.

Typically, the control system allows manual independent repositioning of the handle without effecting corresponding translational movement of the end effector in the second mode. In this second mode, the control system can inhibit independent
25 rotational repositioning of the handle by applying torques to motors of the master controller, by effecting corresponding changes in rotational degrees of freedom of the end effector, or the like. Some embodiments, independent repositioning of the handle is inhibited by driving the handle to a rotational position corresponding to that of the end effector when the control system changes from the second mode back to the first mode.
30 Advantageously, the control system can allow independent repositioning in degrees of freedom which are independent of the specific linkage structure supporting the master input handle or the end effector, allowing only translational repositioning even where the linkage joints effect combinations of rotation and translation.

In another aspect, the invention provides a robotic surgical system comprising a surgical manipulator system. The surgical manipulator system has an image capture device for capturing an image of a surgical site, and at least one medical instrument having at least one rotational degree of freedom of movement and at least one translational degree of freedom of movement. A workstation has a display operatively connected to the image capture device to display the surgical site. The workstation also has at least one master control device operatively associated with the medical instrument to cause selective rotational and translational movement to the instrument in response to inputs to the master control device. A selectively activatable repositioning system is configured to interrupt the operative association between the master control device and the medical instrument. Advantageously, this permits the master control device to be repositioned in at least one translational degree of freedom of movement relative to the medical instrument while the medical instrument is cause to remain stationary. The repositioning system also permits the operative association to be re-established after the master control device has been repositioned. Generally, the repositioning system moves the master control device prior to re-establishing the operative association (during repositioning and/or in response to a signal to re-establish operational association)so as to inhibit repositioning of the master control device in the at least one rotational degree of freedom.

In another aspect, the invention provides a surgical manipulator system having a manipulator moveably supporting at least one surgical instrument with a plurality of degrees of freedom of movement. A master controller workstation is operatively associated with the manipulator to cause selective movement of the instrument in response to inputs from a system operator at the workstation. A selectively activatable repositioning system configured to interrupt the operative association between the workstation and the manipulator so that the surgical instrument can be moved from one position to another, and to re-establish the operative association after the surgical instrument has been repositioned.

Preferably, the repositioning system will comprise an input device adjacent the manipulator, the input device ideally being mounted to the manipulator. The input device may be configured so that the surgical instrument is moveable while the input device is held. The repositioning system will often re-establish the operative association when the input device is released, so that, for example, an assistant at the patient's side can activate the input device and move the manipulator to a desired position with a single

hand while mounting an alternative surgical instrument to the manipulator with the other hand. The surgical instrument may comprise an image capture device or a surgical tool having an end effector configured to treat tissue.

In yet another aspect, the invention provides a robotic surgical system comprising a surgical manipulator system having a moveable image capture device for capturing an image of a surgical site, and at least one medical instrument having a plurality of degrees of freedom of movement. A workstation having a display is operatively connected to the image capture device to display the surgical site. At least one master control device is operatively associated with the medical instrument to cause selective movement to the instrument in response to inputs to the master control device. An image capture device control system is operatively associated with the image capture device to cause selective movement of the image capture device. A selectively activatable repositioning system is configured to interrupt the operative association between the image capture device control and the image capture device so that the image capture device can be moved from one position to another, and to re-establish the operative association after the image capture device has been repositioned.

Generally, the control systems of the present invention may accommodate one or more of these selective repositioning systems so as to allow independent repositioning of an input device handle, an image capture device, and/or a surgical tool for manipulating tissue. Two or more of these repositioning systems may be activated simultaneously to allow simultaneous repositioning of two or more components of the robotic surgical system. The invention also provides methods corresponding to these systems, and tangible media-storing machine-readable code defining program instructions for effecting these methods.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention will now be described, by way of example, and with reference to the accompanying diagrammatic drawings, in which:

Figure 1 is a plan view of a telesurgical system and method for performing a robotic minimally invasive surgical procedure;

Figure 2 shows a three-dimensional view of a control station of a telesurgical system in accordance with the invention;

Figures 3A-C show three-dimensional views of an input device including an articulated arm and wrist to be mounted on the arm for use in the master control station of Fig. 2.

Figure 4 shows a three-dimensional view of a cart of the telesurgical system in accordance with the invention, the cart carrying three robotically controlled manipulator arms, the movement of the arms being remotely controllable from the control station shown in Figure 2;

Figures 5 and 5A show a side view and a perspective view, respectively, of a robotic arm and surgical instrument assembly in accordance with the invention;

Figure 6 shows a three-dimensional view of a surgical instrument of the invention;

Figure 7 shows, at an enlarged scale, a wrist member and end effector of the surgical instrument shown in Figure 6, the wrist member and end effector being movably mounted on a working end of a shaft of the surgical instrument;

Figures 8A-C illustrate alternative end effectors having surfaces for stabilizing and/or retracting tissue.

Figures 9A-E illustrate another cart supporting a fourth robotic manipulator arm in the telesurgical system of Figure 1, and a bracket for mounting a tool on the manipulator arm.

Figure 10 shows a schematic three-dimensional drawing indicating the positions of the end effectors relative to a viewing end of an endoscope and the corresponding positions of master control input devices relative to the eyes of an operator, typically a surgeon;

Figure 11 shows a block diagram indicating one embodiment of a control system of the telesurgical system of the invention;

Figures 11A-D schematically illustrate block diagrams and data transmission time lines of an exemplary controller for flexibly coupling master/slave pairs;

Figure 12 shows a block diagram indicating the steps involved in moving the position of one of the master controls relative to its associated end effector;

Figure 13 shows a control diagram which indicates control steps involved when the master control is moved relative to its associated end effector as indicated in the block diagram of Figure 12;

Figure 14 shows a block diagram indicating the steps involved in moving the position of one of the end effectors relative to its associated master control;

Figure 15 shows a control diagram which indicates control steps involved when the end effector is moved relative to its associated master control as indicated in

5 Figure 14;

Figure 16 shows a block diagram indicating the steps involved in moving the position of a viewing end of an endoscope of the minimally invasive telesurgical system relative to the end effectors;

Figure 17 shows a control diagram which indicates control steps involved when the end of the endoscope is moved relative to the end effectors as indicated in
10 Figure 16;

Figure 18 shows a simplified block diagram indicating the steps involved in realigning a master control device relative to its associated end effector;

Figure 19 shows a block diagram indicating the steps involved in re-
15 connecting a control loop between a master control device and its associated end effector;

Fig. 19A shows a block diagram indicating the steps involved in smoothly recoupling an input device with an end effector so as to avoid inadvertent sudden movements;

Figure 20 shows a schematic diagram indicating an operator of the
20 minimally invasive telesurgical system of the invention at the control station shown in Figure 2;

Figure 21 shows a schematic diagram of an image captured by an endoscope of the minimally invasive telesurgical system of the invention as displayed on a viewer of the system;

25 Figure 21A shows a schematic diagram of another image captured by the endoscope of the minimally invasive telesurgical system of the invention as displayed on the viewer of the system;

Figure 22 shows another image captured by the endoscope of the
30 minimally invasive telesurgical system of the invention as displayed on the viewer of the system;

Figure 22A shows a reference plane indicating a region in dashed lines which corresponds to an area where an automated determination of which of two master control devices of the system is to be associated with which of two slaves of the system is not desired;

Figure 22B shows a block diagram indicating steps involved in determining an association between which of the two master control devices is to be associated with which of the two slaves of the system; and

Figure 22C shows a block diagram indicating steps involved when the association of one of the master control devices with a slave is to be switched or swapped with the association of another master control device and slave;

Figures 23A and 23B illustrate a system and method for performing coronary artery bypass grafting on a beating heart by selectively associating robotic surgical instruments with master input control devices;

Figure 24 shows a block diagram indicating steps involved in a method for handing-off control of robotic tools between a surgeon and an assistant;

Figure 25A is a cross section, looking towards the head, through a chest of a patient body, illustrating an endoscopic coronary artery bypass graft procedure in which the heart is treated by robotic tools introduced via a pattern of apertures on the right side of the patient; and

Figure 25B illustrates an exemplary pattern of four apertures for four robotic endoscopic instruments as used in the procedure of Figure 25A.

Figures 26 and 27 schematically illustrate alternative robotic telesurgical systems.

DESCRIPTION OF THE SPECIFIC EMBODIMENTS

This application is related to the following patents and patent applications, the full disclosures of which are incorporated herein by reference: PCT International Application No. PCT/US98/19508, entitled "*Robotic Apparatus*", filed on September 18, 1998 (Attorney Docket No. 17516-005510PC), U.S. Patent Application Serial No. 60/111,713, entitled "*Surgical Robotic Tools, Data Architecture, and Use*" (Attorney Docket No. 17516-003200), filed on December 8, 1998; U.S. Patent Application Serial No. 60/111,711, entitled "*Image Shifting for a Telerobotic System*" (Attorney Docket No. 17516-002700), filed on December 8, 1998; U.S. Patent Application Serial No. 60/111,714, entitled "*Stereo Viewer System for Use in Telerobotic System*" (Attorney Docket No. 17516-001500), filed on December 8, 1998; U.S. Patent Application Serial No. 60/111,710, entitled "*Master Having Redundant Degrees of Freedom*" (Attorney Docket No. 17516-001400), filed on December 8, 1998, U.S. Patent Application No. 60/116,891, entitled "*Dynamic Association of Master and Slave in a Minimally Invasive Telesurgery System*" (Attorney Docket No. 17516-004700), filed on January 22,

1999; and U.S. Patent No. 5,808,665, entitled “*Endoscopic Surgical Instrument and Method for Use*,” issued on September 15, 1998.

As used herein, first and second objects (and/or their images) appear “substantially connected” if a direction of an incremental positional movement of the first object matches the direction of an incremental positional movement of the second object (often as seen in an image), regardless of scaling between the movements. Matching directions need not be exactly equal, as the objects (or the object and the image) may be perceived as being connected if the angular deviation between the movements remains less than about ten degrees, preferably being less than about five degrees. Similarly, objects and/or images may be perceived as being “substantially and orientationally connected” if they are substantially connected and if the direction of an incremental orientational movement of the first object is matched by the direction of an incremental orientational movement of the second object (often as seen in an image displayed near the first object), regardless of scaling between the movements.

Additional levels of connectedness may, but need not, be provided. “Magnitude connection” indicates substantial connection and that the magnitude of orientational and/or positional movements of the first object and second object (typically as seen in an image) are directly related. The magnitudes need not be equal, so that it is possible to accommodate scaling and/or warping within a magnitude connected robotic system. Orientational magnitude connection will imply substantial and orientational connection as well as related orientational movement magnitudes, while substantial and magnitude connection means substantial connection with positional magnitudes being related.

As used herein, a first object appears absolutely positionally connected with an image of a second object if the objects are substantially connected and the position of the first object and the position of the image of the second object appear at least to substantially match, i.e., to be at the same location, during movement. A first object appears absolutely orientationally connected with an image of the second object if they are substantially connected and the orientation of the first object and the second object at least substantially match during movement.

Referring now to Figure 1, a robotic surgical network 10 includes a master control station 200 and a slave cart 300, along with any of several other additional components to enhance the capabilities of the robotic devices to perform complex surgical procedures. An operator O performs a minimally invasive surgical procedure at

an internal surgical site within patient P using minimally invasive surgical instruments 100. Operator O works at master control station 200. Operator O views a display provided by the workstation and manipulates left and right input devices. The telesurgical system moves surgical instruments mounted on robotic arms of slave cart 300 in response to movement of the input devices. As will be described in detail below, a selectably designated "left" instrument is associated with the left input device in the left hand of operator O, and a selectably designated "right" instrument is associated with the right input device in the right hand of the operator.

As described in more detail in co-pending U.S. Patent Application Serial No. , 09/373,678 entitled "*Camera Referenced Control In A Minimally Invasive Surgical Apparatus*" and filed August 13, 1999, (Attorney Docket No. 17516-002110), the full disclosure of which incorporated herein by reference, a processor of master controller 200 will preferably coordinate movement of the input devices with the movement of their associated instruments so that the images of the surgical tools 100, as displayed to the operator, appear at least substantially connected to the input devices in the hands of the operator. Further levels of connection will also often be provided to enhance the operator's dexterity and ease of use of surgical instruments 100.

Introducing some of the other components of network 10, an auxiliary cart 300A can support one or more additional surgical tools 100 for use during the procedure. One tool is shown here for illustrative purposes only. A first assistant A1 is seated at an assistant control station 200A, the first assistant typically directing movements of one or more surgical instruments not actively being manipulated by operator O via master control station 200. A second assistant A2 may be disposed adjacent patient P to assist in swapping instruments 100 during the surgical procedure. Auxiliary cart 300A may also include one or more assistant input devices 12 (shown here as a simple joy stick) to allow second assistant A2 to selectively manipulate the one or more surgical instruments while viewing the internal surgical site via an assistant display 14. Preferably, the first assistant A1 seated at console 200A views the same image as surgeon seated at console 200. Further preferably, both the instruments of cart 300 and the "assistant" instruments of cart 300A are controlled according to the same camera reference point, such that both surgeon and assistant are able to be "immersed" into the image of the surgical field when manipulating any of the tools.

As will be described hereinbelow, master control station 200, assistant controller 200A, cart 300, auxiliary cart 300A, and assistant display 14 (or subsets of

these components) may allow complex surgeries to be performed by selectively handing-off control of one or more robotic arms between operator O and one or more assistants. Alternatively, operator O may actively control two surgical tools while a third remains at a fixed position, for example, to stabilize and/or retract tissue, with the operator selectively operating the retractor or stabilizer only at designated times. In still further alternatives, a surgeon and an assistant can cooperate to conduct an operation without either passing control of instruments or being able to pass control of the instruments, with both instead manipulating his or her own instruments during the surgery, as will be described below with reference to Figure 26. Although Fig. 1 depicts two surgeon consoles controlling the two cart structures, a preferred embodiment comprises only one console controlling four or more arms on two carts. The scope may optionally be mounted on the auxiliary cart and three tissue manipulator arms may be mounted on the main cart. Generally, the use of robotic systems having four or more arms will facilitate complex robotic surgical procedures, including procedures that benefit from selectable endoscope viewing angles. Methods for using robotic network 10 will be described in more detail following descriptions of the network components. While the network component connections are schematically illustrated in Figures 1, 26, and 27, it should be understood that more complex interconnections between the various network components may be provided.

Component Descriptions

Referring to Figure 2 of the drawings, the control station of a minimally invasive telesurgical system in accordance with the invention is generally indicated by reference numeral 200. The control station 200 includes a viewer or display 202 where an image of a surgical site is displayed in use. A support 204 is provided on which an operator, typically a surgeon, can rest his or her forearms while gripping two master controls (Figures 3A and 3B), one in each hand. The master controls are positioned in a space 206 inwardly beyond the support 204. When using control station 200, the surgeon typically sits in a chair in front of the control station 200, positions her eyes in front of the viewer 202, and grips the master controls, one in each hand, while resting her forearms on the support 204.

An example of one of the master control input devices is shown in Figures 3A-C, and is generally indicated by reference numeral 210. The master control device generally comprises an articulate positioning arm 210A supporting orientational

gimbals 210B. Gimbals 210B (shown most clearly in Figure 3B) have a plurality of members or links 212 connected together by joints 214, typically by rotational joints. The surgeon grips the master control 210 by positioning his or her thumb and index finger over a grip actuation handle, here in the form of a grip handle or pincher formation 216.

5 The surgeon's thumb and index finger are typically held on the pincher formation by straps (not shown) threaded through slots 218. To move the orientation of the end effector, the surgeon simply moves the pincher formation 216 to the desired end effector orientation relative to the image viewed at the viewer 202, and the end effector orientation is caused to follow the orientation of the pincher formation. Appropriately positioned positional sensors, e.g., encoders, or potentiometers, or the like, are coupled to each joint of gimbals 210B, so as to enable joint positions of the master control to be determined as also described in greater detail herein below.

Gimbals 210B are similarly repositioned by movement of pincher formation 216, and this positional movement is generally sensed by articulation of input arm 210A as shown in Figure 3A. Reference numerals 1-3 indicate orientational degrees of freedom of gimbals 210B, while numeral 4 in Figures 3A and 3B indicates the joint with which the master control and the articulated arm are connected together. When connected together, the master control 210 can also displace angularly about axis 4.

The articulated arm 210A includes a plurality of links 220 connected together at joints 222. Articulated arm 210A has appropriately positioned electric motors to provide for feedback as described in greater detail below. Furthermore, appropriately positioned positional sensors, e.g., encoders, or potentiometers, or the like, are positioned on the joints 222 so as to enable joint positions of the master control to be determined as further described herein below. Axes A, B, and C indicate the positional degrees of freedom of articulated arm 210A. In general, movement about joints of the master control 210B primarily accommodates and senses orientational movement of the end effector, and movement about the joints of arm 210A primarily accommodates and senses translational movement of the end effector. The master control 210 is described in greater detail in U.S. Provisional Patent Application Serial No. 60/111,710, and in U.S. Patent Application No. _____, filed concurrently herewith (Attorney Docket No. 17516-001410), the full disclosures of which are incorporated herein by reference.

As described more fully in co-pending U.S. Patent Application Serial No. 09/373,678, the full disclosure of which is incorporated herein by reference, the orientation of the viewer relative to the master control input devices will generally be

compared with the position and orientation of the end effectors relative to a field of view of the image capture device. The relative locations of the input devices can be derived from knowledge regarding the input device linkage joint configurations (as sensed by the joint sensors), the construction and design of the master controller structure, and in some cases, calibration measurements taken from a specific master control console system after fabrication. Such calibration measurements may be stored in a non-volatile memory of the console.

In Figure 4 of the drawings, the cart 300 is adapted to be positioned close to a surgical platform in preparation for surgery, and can then be caused to remain stationary until a surgical procedure has been completed. The cart 300 typically has wheels or castors to render it mobile. The control station 200 may optionally be positioned remote from the cart 300, but will often be in or adjacent the operating room. The cart 300 carries three robotic arm assemblies. One of the robotic arm assemblies, indicated by reference numeral 302, is arranged to hold an image capturing device 304, e.g., an endoscope, or the like. Each of the two other arm assemblies 310 is arranged to carry a surgical instrument 100. The robotic arms are supported by positioning linkages 395, which can be manually positioned and then locked in place before (or re-positioned during) the procedure.

The positioning linkages or "set-up joints" are described in Provisional Application Serial No. 60/095,303, the full disclosure of which is incorporated herein by reference. Preferably, the set-up joints include joint sensors which transmit signals to the processor indicating the position of the remote center of rotation. It should be noted that the manipulator arm assemblies need not be supported by a single cart. Some or all of the manipulators may be mounted to a wall or ceiling of an operating room, separate carts, or the like. Regardless of the specific manipulator structures or their mounting arrangement, it is generally preferable to provide information to the processor regarding the location of insertion/pivot points of the surgical instruments into the patient body. The set-up joint linkages need not have joint drive systems but will often include a joint brake system, as they will often hold the manipulators in a fixed position during some or all of a surgical procedure.

The endoscope 304 has a viewing end 306 at a remote end of an elongate shaft. The elongate shaft of endoscope 304 permits it to be inserted into an internal surgical site of a patient's body. The endoscope 304 is operatively connected to the viewer 202 to display an image captured at its viewing end 306 on the viewer 202.

Each robotic arm 302, 310 can be operatively connected to one or more of the master controls 210 so that the movement of instruments mounted on the robotic arms is controlled by manipulation of the master controls. The instruments 100 carried on the robotic arm assemblies 310 have end effectors, generally indicated at 102, which are mounted on wrist members, the wrists in turn being pivotally mounted on distal ends of elongate shafts of the instruments. It will be appreciated that the instruments have elongate shafts to permit them to be inserted into an internal surgical site of a patient's body. Movement of the end effectors relative to the ends of the shafts of the instruments is also controlled by the master controls.

In Figures 5 and 5A of the drawings, one of the robotic manipulator arm assemblies 310 is shown in greater detail. Assembly 310 includes an articulated robotic arm 312, and a surgical instrument, schematically and generally indicated by reference numeral 100, mounted thereon.

Figure 6 indicates the general appearance of the surgical instrument 100 in greater detail. The surgical instrument 100 includes an elongate shaft 104. The wrist-like mechanism, generally indicated by reference numeral 106, is located at a working end of the shaft 104. A housing 108, arranged to releasably couple the instrument 100 to the robotic arm 312, is located at an opposed end of the shaft 104. In Figure 6, and when the instrument 100 is coupled or mounted on the robotic arm 312, the shaft 104 extends along an axis indicated at 109.

Referring again to Figures 5 and 5A, the instrument 100 is typically releasably mounted on a carriage 314, which is driven to translate along a linear guide formation 316 of the arm 312 in the direction of arrows P. The robotic arm 312 is typically mounted on a base by means of a bracket or mounting plate 317, which is affixed to the passively movable set-up joints 395. Set-up joints 395 are held in a fixed configuration during manipulation of tissue by a set-up joint brake system. The base may be defined by the mobile cart or trolley 300, which is retained in a stationary position during a surgical procedure.

The robotic arm 312 includes a cradle, generally indicated at 318, an upper arm portion 320, a forearm portion 322 and the guide formation 316. The cradle 318 is pivotally mounted on the plate 317 in gimbaled fashion to permit rocking movement of the cradle in the direction of arrows 326 as shown in Figure 5, about a pivot axis 328. The upper arm portion 320 includes link members 330, 332 and the forearm portion 322 includes link members 334, 336. The link members 330, 332 are pivotally mounted on

the cradle 318 and are pivotally connected to the link members 334, 336. By use of this linkage, irrespective of the movement of the robotic arm 312, a pivot center 349 remains in the same position relative to plate 317 with which the arm 312 is mounted. In use, the pivot center 349 is positioned at an aperture or a port of entry into a patient's body when an internal surgical procedure is to be performed.

While this "remote" center of motion-type arrangement for robotic manipulation is described in connection with the preferred embodiments of this invention, the scope of the inventions disclosed herein is not so limited, encompassing other types of arrangements such as manipulator arms having passive or natural centers of motion at the point of insertion into a patient body.

The robotic arm 312 provides three degrees of freedom of movement to the surgical instrument 100 when mounted thereon. These degrees of freedom of movement are firstly the gimbaled motion indicated by arrows 326, pivoting movement as indicated by arrows 327 and the linear displacement in the direction of arrows P. These three degrees of freedom of movement are primarily coupled to translational degrees of movement of the end effector, although some rotational coupling may be present. Movement of the arm as indicated by arrows 326, 327 and P is controlled by appropriately positioned electrical motors which respond to inputs from an associated master control to drive the arm 312 to a required position as dictated by movement of the master control. Appropriately positioned sensors, e.g., potentiometers, or the like, are provided on the arm to determine joint positions as described in greater detail herein below.

Referring now to Figure 7 of the drawings, the wrist mechanism 106 will now be described in greater detail. In Figure 7, the working end of the shaft 104 is indicated at 110. The wrist mechanism 106 includes a wrist member 112. One end portion of the wrist member 112 is pivotally mounted in a clevis, generally indicated at 117, on the end 110 of the shaft 104 by means of a pivotal connection 114. The wrist member 112 can pivot in the direction of arrows 156 about the pivotal connection 114.

An end effector, generally indicated by reference numeral 102, is pivotally mounted on an opposed end of the wrist member 127. The end effector 102 is in the form of, e.g., a clip applier for anchoring clips during a surgical procedure. Accordingly, the end effector 102 has two elements 102.1, 102.2 together defining a jaw-like arrangement. It will be appreciated that the end effector can be in the form of any surgical tool having two members which pivot about a common pivotal axis, such as scissors, pliers for use as

needle drivers, or the like. Instead, it can include a single working member, e.g., a scalpel, cautery electrode, or the like. Alternative non-articulated tools may also be used, including tools for aspiration and/or irrigation, endoscopes, or the like. When a tool other than a clip applier is required during the surgical procedure, the tool 100 is simply
5 removed from its associated arm and replaced with an instrument bearing the required end effector, e.g., a scissors, or pliers, or the like.

The end effector 102 is pivotally mounted in a clevis, generally indicated by reference numeral 119, on an opposed end of the wrist member 112, by means of a pivotal connection 160. Elements 102.1, 102.2 are angularly displaceable about the
10 pivotal connection 160 toward and away from each other as indicated by arrows 162, 163. It will further be appreciated that the elements 102.1, 102.2 can be displaced angularly about the pivotal connection 160 to change the orientation of the end effector 102 as a whole, relative to the wrist member 112. Thus, each element 102.1, 102.2 is angularly displaceable about the pivotal connection 160 independently of the other, so that the end
15 effector 102, as a whole, is angularly displaceable about the pivotal connection 160 as indicated in dashed lines in Figure 7. Furthermore, the shaft 104 is rotatably mounted on the housing 108 for rotation as indicated by the arrows 159. Thus, the end effector 102 has three degrees of freedom of movement relative to the arm 112 in addition to actuation of the end effector, preferably namely, rotation about the axis 109 as indicated by arrows
20 159, angular displacement as a whole about the pivot 160 and angular displacement about the pivot 114 as indicated by arrows 156. Other wrist structures and combinations of joints also fall within the scope of the present inventions, however. For example, while this arrangement and these resulting degrees of freedom of movement are preferred, a wrist having fewer degrees of freedom of movement, such as a single distal articulating
25 joint, or a wrist having other singularities, may also be used, as desired.

The three degrees of freedom of movement of instrument 100 are primarily coupled to orientational degrees of freedom of movement of the end effector. This is somewhat a simplification, as movement about these three axes will result in some change in position of the end effector. Similarly, movement about the above-described
30 translational axes may cause some changes in orientation. It will be appreciated that orientational movement of the end effector, like translational movement, is controlled by appropriately positioned electrical motors which respond to inputs from the associated master control to drive the end effector 102 to a desired position as dictated by movement of the master control. Furthermore, appropriately positioned sensors, e.g., encoders, or

potentiometers, or the like, are provided to determine joint positions as described in greater detail herein below. In this specification the actuation or movement of the end effectors relative to each other in the directions of arrows 62, 63 is not regarded as a separate degree of freedom of movement.

5 Tissue stabilizer end effectors 120a, b, and c, referred to generally as tissue stabilizers 120, are illustrated in Figures 8A-C. Tissue stabilizers 120 may have one or two end effector elements 122 that preferably are pivotally attached to the distal end of the shaft or wrist of a surgical instrument and are moveable with respect to one another, and that preferably comprise tissue-engaging surfaces 124. The tissue-engaging surfaces
10 optionally include protrusions, ridges, vacuum ports, or other surfaces adapted so as to inhibit movement between the engaged tissue and the stabilizer, either through pressure applied to the engaged tissue or vacuum applied to draw the tissue into an at least partially stabilized position, or a combination of both pressure and vacuum. The ideal tissue engaging surface will constrain and/or reduce motion of the engaged tissue in the
15 two lateral (sometimes referred to as the X and Y) axes, along the tissue-engaging surface, and the stabilizer configuration and engagement with the tissue will at least partially decrease motion normal to the surface. Other configurations for traditional stabilizers are known to those of skill in the art, such as the Octopus II of Medtronic, Inc. and various HeartPort, Inc. and CardioThoracic Systems stabilizers having multipronged
20 and doughnut configurations. These manners of contacting tissue allow stabilizers 120 to firmly engage a moving tissue such as a beating heart of a patient and reduce movement of the tissue adjacent the stabilizer.

To facilitate performing a procedure on the stabilized tissue, an opening 126 may be formed in an individual stabilizer element 122, and/or between
25 independently moveable end effector elements. As illustrated in Figure 8B, stabilizer 120b includes cooperating tissue grasping surfaces 128 disposed between stabilizer end effector elements 122. This allows the stabilizer to grasp tissues, providing a dual function robotic stabilizer/grasper tool. Stabilizer 120b may be used, for example, as a grasper while harvesting and/or preparing an internal mammary artery (IMA) for a
30 coronary artery bypass graft (CABG) procedure, and/or to hold the IMA during formation of the anastomosis on the stabilized beating heart.

In general, tissue stabilizers 120 will have a sufficiently small profile, when aligned with shaft 104 of instrument 100, to allow the stabilizer to advance axially through a cannula. Similar (or modified) end effectors having high friction tissue-

engaging surfaces may be used as retractors to hold tissue clear of a surgeon's line of sight during a procedure.

Referring now to Figure 8C, and generally for the robotic endoscopic stabilizers disclosed herein, each stabilizer may comprise an irrigation port 125, the port preferably in fluid communication with a lumen integrated into the shaft of the stabilizer tool. While an irrigation and/or aspiration capability is particularly beneficial when incorporated into a stabilizer, such capabilities may also be incorporated into the shaft of any robotic surgical tool, as desired. The port system, comprising a lumen preferably situated inside the shaft of the stabilizer and extending out of an aperture or port in the distal portion of the shaft, may be used to perform a number of tasks during a surgical procedure (e.g., a beating heart procedure) in which stabilization of tissue is desired. Those tasks may include removing undesired fluid from the surgical site (either through suction to outside the patient's body), blowing the fluid into some other portion of the surgical site, and/or delivering fluid (such as spray humidified carbon dioxide) to clear the surgical site of material (such as body fluids which might otherwise interfere with the surgeon's view). Preferably, at least the distal portion of the port system is flexible to permit bending. The exemplary port structure will be malleable or plastically deformable enough that it will hold its position when repositioned.

To take advantage of the irrigation aspect of this multi-functional stabilizer, the stabilizer is inserted with the distal external portion of the irrigation device preferably flush with the shaft of the stabilizer. After the stabilizer has reached the surgical site, the operator may reposition the irrigation port distal end with one of the other surgical manipulators by grasping the port structure and moving it to a desired location and/or orientation relative to shaft 104, wrist 106, or end effector element 122 (depending on the structure to which the port is mounted). The device may remain in that location for the duration of the surgery, or may be moved around as desired. In addition to simply being moveable at the surgical site, the device also may be extendable from/retractable into the stabilizer shaft, so that the distal end can be moved towards or away from the surgical site itself, as desired.

An example of a preferred auxiliary cart 300A is seen in more detail in Figures 9A and B. Auxiliary cart 300A includes a simple linkage 350 with sliding joints 352 which can be releasably held in a fixed configuration by latches 354. Linkage 350 supports an auxiliary remote center manipulator arm 302A having a structure similar to arm 302 used to support the endoscope on cart 300. (See Figure 4.)

The linkage structure of auxiliary arm 302A is described more fully in co-pending U.S. Patent Application Serial No. 60/112,990, filed on December 16, 1998, the full disclosure of which is incorporated herein by reference. Generally, auxiliary arm 302A effectively includes a parallel linkage mechanism providing a remote center of spherical rotation 349 at a fixed location relative to base 317, similar to that described above with reference to arm 312 in Figure 5. Although this arm is described as preferably being of different structure than other instrument manipulator arms also described herein, it should be understood that another manipulator arm can also be used either to support an endoscope or to serve as the fourth arm on the auxiliary cart 300A.

Sliding joints 352 and wheels 356 (which can also be releasably locked in a fixed configuration by latches 354) allow remote center or fulcrum 349 to be positioned at an insertion point into a patient body using translational movement along X, Y, and Z axes. Auxiliary arm 302A may optionally be actively driven so as to translationally position a shaft of a surgical instrument within a patient body. Alternatively, auxiliary arm 302A may be used as a passive manipulator arm. Auxiliary arm 302A (like all manipulator arms of the robotic network) preferably includes a repositioning configuration input device or button 358, ideally disposed on a manual positioning handle 360. When repositioning button 358 is depressed, the joints of auxiliary arm 302A move freely so as to pivot the arm about fulcrum 349 manually. Once actuator 358 is released, auxiliary arm 302A remains in a substantially fixed configuration. The arm will resist movement until repositioning button 358 is again held down, or until the arm receives an actuation signal from an associated master control input device. Hence, auxiliary cart 300A may be used to support a surgical instrument such as an endoscope, a stabilizer, a retractor, or the like, even if not actively driven under direction of an input device.

Manual repositioning of the supported surgical instrument will generally be performed by an assistant under the direction of a surgeon in charge of the surgical procedure. Typically, even when the set-up joints 395, cart linkages 350, arms 302, 312, and/or other structures of the robotic system support the end effectors in a fixed configuration, the brake or motor drive systems inhibiting movement of the instruments can be safely overridden using manual force without damaging the robotic system. This allows repositioning and/or removal of the instruments if a failure occurs. Preferably, the override force will be sufficient to inhibit inadvertent movement from accidental bumping, interference between manipulators, and the like.

Auxiliary arm 302A and arm 302 used to support endoscope 304 need not necessarily include a drive system for articulating a wrist and/or end effectors within the patient body, unless, e.g., a wrist is to be used in connection with a stabilizer to improve positioning of the particular tissue to be stabilized. When auxiliary cart 300A is to be used to actively drive an articulated tool under the direction of an operator O or assistant via a processor, arm 302 may optionally be replaced by arm 312. Alternatively, where the auxiliary cart is to be used as a passive structure to hold an articulated surgical instrument at a fixed position and configuration within a patient body, a manual tool articulation bracket 370 may be used to mount the tool 100 to auxiliary arm 302A. The manual tool bracket 370 is illustrated in Figures 9C-9E.

As can be understood with references to Figures 9C and 9D, bracket 370 comprises a plate 372 with sidewalls which fittingly receive housing 108 of tool 100. Discs 374 have drive surfaces which drivingly engage the drive system of tool 100 so as to rotate shaft 104 about its axis, articulate the end effector about the wrist, and move the first and second end effector elements, as described above.

As seen most clearly in Figure 9E, the rotational position of discs 374 can be changed by manually rotating adjustment knobs 376, which are rotationally coupled to the discs. Once the instrument 100 is in the desired configuration, lock nuts 378 may be tightened against washers 379 to rotationally affix knobs 376 and discs 374. In the exemplary embodiment, bracket 372 comprises a polymer, while knobs 376 and nuts 378 may be polymeric and/or metallic. Washer 379 may comprise a low friction polymer, ideally comprising a PTFE such as Teflon™, or the like. While the disclosure herein shows a preferred embodiment for manual manipulation of a stabilizer by a surgical assistant, it should be apparent that the stabilizer might just as easily be controlled from a remote robotic control console, from which the operator would manipulate the stabilizer and any associated wrist in the same way as other instruments are controlled, as herein described.

Telesurgical Methods and Component Interactions

In use, the surgeon views the surgical site through the viewer 202. The end effector 102 carried on each arm 312, 302, 302A is caused to perform movements and actions in response to movement and action inputs of its associated master control. It will be appreciated that during a surgical procedure images of the end effectors are captured by the endoscope together with the surgical site and are displayed on the viewer

so that the surgeon sees the movements and actions of the end effectors as he or she controls such movements and actions by means of the master control devices. The relationship between the end effectors at the surgical site relative to the endoscope tip as viewed through the viewer and the position of the master controls in the hands of the surgeon relative to the surgeon's eyes at the viewer provides an appearance of at least a substantial connection between the master controls and the surgical instrument for the surgeon.

To provide the desired substantial connection between the end effector images and the master controller input devices, the processor of master control station 200 and/or assistant control station 200A will generally map the internal surgical worksite viewed by the endoscope onto the master controller work space in which the operator and/or assistant moves his or her hands. The position of the arms holding the surgical tools relative to the arm holding the endoscope in use may be used to derive the desired coordinate transformations so as to provide the desired level of substantial connectedness, as more fully explained in co-pending U.S. Patent Provisional Application Serial No. 60/128,160, previously incorporated herein by reference.

Where a tool is to be viewed through an endoscope, and the tool and endoscope are supported by independent support structures (for example, when viewing a tool supported by arm 312 within the internal surgical site via an endoscope supported by auxiliary cart 300A) it is particularly beneficial to have a known orientation between the two independent support structures to allow the desired transformations to be derived. This may be provided, for example, by ensuring that the base structure of cart 300 is accurately parallel to the base structure of auxiliary cart 300A. As positional transformations and modifications are relatively straightforward when orientations are accurately aligned, this allows a processor to provide substantial connection despite the separately mounted robotic network components.

The operation of telesurgical robotic network 10 will first be explained with reference to interaction between master control station 200 and cart 300. Many of the aspects of this interaction appear in the interactions among the remaining network components.

Master-Slave Controller

In Figure 10, the Cartesian space coordinate system is indicated generally by reference numeral 902. The origin of the system is indicated at 904. The system 902

is shown at a position removed from the endoscope 304. In the minimally invasive telesurgical system of the invention, and for purposes of identifying positions in Cartesian space, the origin 904 is conveniently positioned at the viewing end 306. One of the axes, in this case the Z-Z axis, is coincident with the viewing axis 307 of the endoscope.

- 5 Accordingly, the X-X and Y-Y axes extend outwardly in directions perpendicular to the viewing axis 307.

It will be appreciated that in the case of angular displacement of the endoscope to vary the orientation of the displayed image as described above, the reference plane defined by the X-X and Y-Y axis is angularly displaced together with the
10 endoscope.

As mentioned earlier, when the surgical instruments are mounted on the arms 112, a fulcrum 349 or pivot point is defined for each arm assembly 310. Furthermore, as also already mentioned, each fulcrum 349 is positioned at a port of entry into the patient's body. Thus, movements of the end effectors at the surgical site is
15 caused by angular displacements about each fulcrum 349. As described above, the location of the fulcrums may be sensed using joint sensors of the set-up joints, or using a variety of alternative position sensing systems.

When the remote center or fulcrum positions relative to the viewing end 306 of the endoscope 304 are determined, the coordinates in the X-X and Y-Y plane of the Cartesian coordinate system 902 are determined. It will be appreciated that these
20 (X,Y) coordinates of each fulcrum 349 can vary depending on the chosen entry ports to the surgical site. The location of these entry ports can vary depending on the surgical procedure to be performed. It will further be appreciated that the (X,Y) coordinates of each fulcrum 349 can readily be determined with reference to the coordinate system 902
25 by means of the position sensors at the various pivot points on each robotic arm 112 since the endoscope 304 and the arms 310 are mounted on the same cart 300. Naturally, the endoscope arm 302 is also provided with appropriately positioned positional sensors. Thus, to determine the (X,Y) coordinates of each fulcrum 349, relative to the coordinate system 902, the position of the coordinate system 902 can be determined relative to any
30 arbitrary point in space by means of the positional sensors on the endoscope arm 302 and the positions of each fulcrum relative to the same arbitrary point can readily be determined by means of the positional sensors on each robotic arm 112. The positions of each fulcrum 349 relative to the coordinate system 902 can then be determined by means of routine calculation.

With reference to Figure 11, a control system defining a control loop which links master control inputs to end effector outputs, and vice versa for feedback, is schematically indicated by reference numeral 400. Master control inputs and corresponding end effector outputs are indicated by arrows AB and end effector inputs and corresponding master control outputs in the case of feedback is indicated by arrows BA.

In this specification, for the sake of clarity, positions sensed by the encoders on the master which relate to joint positions are referred to as "joint space" positions. Similarly, for the sensors on the joints of the robotic arm and the wrist mechanism, positions determined by these sensors are also referred to as "joint space" positions. The robotic arm and wrist mechanism will be referred to as the slave in the description which follows. Furthermore, references to positions and positioned signals may include orientation, location, and/or their associated signals. Similarly, forces and force signals may generally include both force and torque in their associated signals.

For ease of explanation, the system 400 will be described from an initial condition in which the master is at an initial position and the slave is at a corresponding initial position. However, in use, the slave tracks master position in a continuous manner.

Referring to the control system 400, the master is moved from the initial position to a new position corresponding to a desired position of the end effector as viewed by the surgeon in the image displayed on the viewer 202. Master control movements are input by a surgeon at 402, as indicated by arrow AB1 by applying a force to the master control at 404 to cause the master control to move from its initial position to the new position.

As the master is moved, signals e_m from the encoders on the master is input to a master input controller at 406 as indicated by arrow AB2. At the master input controller 406, the signals e_m are converted to a joint space position θ_m corresponding to the new position of the master. The joint space position θ_m is then input to a master kinematics converter 408 as indicated by arrow AB3. At 408 the joint position θ_m is transformed into an equivalent Cartesian space position x_m . This is optionally performed by a kinematic algorithm including a Jacobian transformation matrix, inverse Jacobian (J^{-1}), or the like. The equivalent Cartesian space position x_m is then input to a bilateral controller at 410 as indicated by arrow AB4.

Position comparison and force calculation may, in general, be performed using a forward kinematics algorithm which may include a Jacobian matrix. Forward

kinematics algorithm generally makes use of a reference location, which is typically selected as the location of the surgeon's eyes. Appropriate calibration or appropriately placed sensors on console 200 can provide this reference information. Additionally, the forward kinematics algorithm will generally make use of information concerning the lengths and angular offsets of the linkage of the master input device 210. More specifically, the Cartesian position x_m represents the distance of the input handle from, and the orientation of the input handle relative to, the location of the surgeon's eyes. Hence, x_m is input into bilateral controller 410 as indicated by AB4.

In a process similar to the calculations described above, the slave location is also generally observed using sensors of the slave system. In the exemplary embodiment, the encoder signal e_s are read from the slave joint sensors at 416 as indicated by BA2, and are then converted to joint space at step 414. As indicated by BA3, the joint space position of the slave is also subjected to a forward kinematics algorithm at step 412. Here, the forward kinematics algorithm is preferably provided with the referenced location of tip 306 of endoscope 304. Additionally, through the use of sensors, design specifications, and/or appropriate calibration, this kinematics algorithm incorporates information regarding the lengths, offsets, angles, etc., describing the linkage structure of patient cart 300, set-up joints 395, and robotic manipulator arms 310, so that the slave Cartesian position x_s transferred at BA4 is measured and/or defined relative to the endoscope tip.

At bilateral controller 410, the new position of the master x_m in Cartesian space relative to the surgeon's eyes is compared with the initial position x_s of the instrument tip in Cartesian space relative to the camera tip. This relationship is depicted in Fig. 10 showing the triangle connecting the surgeon's eye and the master controllers in the hands of the surgeon, as well as the triangle coupling camera tip 306 and the end effectors of tools 104. Advantageously, the comparison of these relative relationships occurring in controller 410 can account for differences in scale between the master controller space in which the input device is moved as compared with the surgical workspace in which the end effectors move. Similarly, the comparison may account for possible fixed offsets, should the initial master and slave positions not correspond.

At 410, the new position x_m of the master in Cartesian space is compared with the initial position of the slave, also in Cartesian space. It will be appreciated that the positions of the master and slave in Cartesian space are continually updated in a memory. Thus, at 410, the initial position of the slave in Cartesian space is downloaded

from the memory so as to compare it with the new position of the master in Cartesian space. Thus, the initial position of the slave in Cartesian space was derived from the joint space position of the slave when both the master and the slave were at their initial positions. It will further be appreciated that, at 410, and where the position of the master in Cartesian space conforms with a corresponding position of the slave in Cartesian space, no positional deviation results from the comparison at 410. In such a case no signals are sent from 410 to cause movement of the slave or the master.

Since the master has moved to a new position, a comparison of its corresponding position x_m in Cartesian space with the Cartesian space position of the slave corresponding to its initial position, yields a positional deviation. From this positional deviation in Cartesian space, a force f_s in Cartesian space is computed at 410 which is necessary to move the slave position in Cartesian space to a new position corresponding to the new position of the master x_m in Cartesian space. This computation is typically performed using a proportional integral derivative (P.I.D.) controller. This force f_s is then input to a slave kinematics converter 412 as indicated by arrow AB5. Equivalent joint torques τ_s are computed in the slave kinematics module, typically using a Jacobian transpose method. This is optionally performed by a Jacobian Transpose (J^T) controller.

The torques τ_s are then input to a slave output converter at 414 as indicated by arrow AB6. At 414 currents are computed. These currents are then forwarded to the electrical motors on the slave at 416 as indicated by arrow AB7. The slave is then caused to be driven to the new position x_e which corresponds to the new position into which the master has been moved.

The control steps involved in the control system 400 as explained above are typically carried out at about 1300 cycles per second or faster. It will be appreciated that although reference is made to an initial position and new position of the master, these positions are typically incremental stages of a master control movement. Thus, the slave is continually tracking incremental new positions of the master.

The control system 400 makes provision for force feedback. Thus, should the slave, typically the end effector, be subjected to an environmental force f_e at the surgical site, e.g., in the case where the end effector pushes against tissue, or the like, such a force is fed back to the master control. Accordingly, when the slave is tracking movement of the master as described above and the slave pushes against an object at the

surgical site resulting in an equal pushing force against the slave, which urges the slave to move to another position, similar steps as described above take place.

The surgical environment is indicated at 418 in Figure 11. In the case where an environmental force f_e is applied on the slave, such a force f_e causes displacement of the end effector. This displacement is sensed by the encoders on the slave 416 which generate signals e_s . Such signals e_s are input to the slave input converter 414 as indicated by arrow BA2. At the slave input 414 a position θ_s in joint space is determined resulting from the encoder signals e_s . The joint space position θ_s is then input to the slave kinematics converter at 412 and as indicated by arrow BA3. At 412 a Cartesian space position x_s corresponding to the joint space position θ_s is computed and input to the bilateral controller at 410 as indicated by arrow BA4. The Cartesian space position x_s is compared with a Cartesian space position x_m of the master and a positional deviation in Cartesian space is computed together with a force f_m required to move the master into a position in Cartesian space which corresponds with the slave position x_s in Cartesian space. The force f_m is then input to the master kinematics converter at 408 as indicated by arrow BA5.

From the f_m input, desired torque values τ_m are determined at 408. This is typically performed by a Jacobian Transpose (J^T) controller. The torque values are then input to the master output converter at 406 as indicated by arrow BA6. At 406, master electric motor currents i_m are determined from the torque values τ_m and are forwarded to the master at 404 and as indicated by arrow BA7 to cause the motors to drive the master to a position corresponding to the slave position.

Although the feedback has been described with respect to a new position desired by the master to track the slave, it will be appreciated that the surgeon is gripping the master so that the master does not necessarily move. The surgeon however feels a force resulting from feedback Torques on the master which he counters because he is holding onto the master.

The discussion above relating to the control system 400 provides a brief explanation of one type of control system which can be employed. It will be appreciated that instead of using a Jacobian Transpose controller, an Inverse Jacobian Controller arrangement can be used. When using an inversed Jacobian controller, bilateral controller 410 may output a Cartesian slave position command x_{sd} at AB5 to the kinematics module 412, with the Cartesian slave position command indicating the desired

position of the slave. Kinematics algorithm module 412 may then use, for example, an inverse Jacobian algorithm to determine a desired joint space position θ_{sd} which can be compared against the initial joint space position of the slave θ_s . From this comparison, joint torques may be generated to compensate for any positioning errors, with the joint torques passed via AB6 to the slave input/output module 414 as described above.

It should also be noted that control system 400 may couple actuation of the master handle (in the exemplary embodiment, variation of the gripping angle defined between grip members 218 as shown in Fig. 3B) to articulation of the end effector (in the exemplary embodiment, opening and closing the end effector jaws by varying the end effector angle between end effector elements 102.1, 102.2 as illustrated in Fig. 7) in the matter described above, by including the master grip input and the end effector jaw actuation in the joint and Cartesian position effectors, equivalent torque vectors, and the like, in the calculations which have been described.

It should be understood that additional controllers or controller modules may be active, for example, to provide friction compensation, gravity compensation, active driving of redundant joint linkage systems so as to avoid singularities, and the like. These additional controllers may apply currents to the joint drive systems of the master and slaves. The additional functions of these added controllers may remain even when the master/slave control loop is interrupted, so that termination of the master/slave relationship does not necessarily mean that no torques are applied.

An exemplary controller block diagram and data flow to flexibly couple pairs of master controllers with manipulator arms are shown in Figs. 11A-11D. As described above, the operator 402 manipulates manipulators 404, here inputting actuation forces against both the left and right master manipulators $f_h(L, R)$. Similarly, both left and right positions of the master input devices will also be accommodated by the control system, as will forces and positions of four or more slave manipulator arms $f_e(1, 2, 3, \text{ and } 4)$, $x_e(1, 2, 3, \text{ and } 4)$. Similar left, right, and slave notations apply throughout Figs. 11A-11D.

The encoder increments from each joint of the master input devices 404 and the slave manipulators 416 are all input into a servocontrol input pre-processor SCI. In some or all of the joints of the master or slave structures, this information may be provided in an alternative format, such as with an analogue signal (optionally providing absolute position indication) from a Hall effect transducer, a potentiometer, or the like.

Where at least some of the signals transmitted from master input devices 404 or slave manipulators 416 comprise encoder increments, pre-processor SCI may include one or more accumulators 1002 as illustrated in Fig. 11B. Positive and/or negative encoder increments are counted between servocycle transfer requests 1004, which are provided from a servo timing generator STG are accumulated in a first register 1006. After receipt of transfer request 1004, the accumulated encoder increments from throughout the servocycle are transferred to second register 1008.

As schematically illustrated in Fig. 11C, the transfer request is preferably offset from an encoder increment clock so as to avoid inadvertent encoder reading errors during servocycle data transfer. In other words, to avoid losing encoder increments during data transfer, an asynchronous transfer request/encoder increment sample rate is preferably provided, as illustrated in Fig. 11C. The sample rate will often be higher than the rate at which the encoder can produce increments, and the accumulators will generally hold incremental position information for all encoder-equipped freely moveable joints of the input and slave manipulators over a servocycle, the servocycle preferably having a frequency of over 900 Hz, more preferably having a frequency of 1,000 Hz or more, often having a frequency of at least about 1,200 Hz, and ideally having a frequency of about 1,300 Hz or more.

Preferably, an accumulator 1002 will be included in pre-processor SCI for each encoder of the master input devices 404 and slave manipulators 416. Each encoder accumulator will preferably accommodate at least a 12-bit joint position signal, and in many cases will accommodate a 14-bit joint position signal. Where analogue position signals are provided, they will typically be converted to digital signals at or before storage in the pre-processor SCI, with as many as 48 joint signals or more being provided in the exemplary pre-processor.

Referring now to Figs. 11A and 11D, and first concentrating on transmission to and from a first bilateral controller CE1 during a servocycle, joint positional information e_m, e_s for a particular master input device 404/slave manipulator 416 pair is retrieved in response to a servointerrupt signal 1010 from the servo timing generator STG. The control processor CTP may transform these joint position signals to the desired coordinate reference frame, or may alternatively transfer this information in joint space on to the bilateral controller CE1 for conversion to the desired reference frame. Regardless, the position is preferably transmitted from the

control processor CTP to the bilateral controller CE1 using a direct memory access DMA controller or other high-speed data transmission system.

Once the positional information has been transferred from the control processor CTP to controller CE1 at DMA interrupt 1012 (see Fig. 11D), the controller
5 processes the positional information, comparing the end effector positions in the surgical workspace with the input device positions (including both location and orientation) in the master controller workspace.

As more fully explained in co-pending U.S. Patent Application Serial No. 09/373,678, filed August 13, 1999, the full disclosure of which is incorporated herein
10 by reference, the surgical and controller se workspaces may be scaled and positioned relative to each other as desired, often using positional information provided by the sensors of the set-up joints, and incorporating calibration and/or assembly information of the master control console so as to identify the location and/or orientation of the master input device relative to the viewer. In general, as the structure supporting the image
15 capture device and end effectors on the slave side are known, and as the location of the viewer relative to the master input device can be calculated from similar knowledge regarding the lengths of the master input lengths, the master controller joint angles, and the like, an appropriate coordination transformation may be derived so as to mathematically couple the master space of the master control workstation and the slave
20 space in the surgical environment. The information on both the master and slave linkages in structure may be based on a model of these linkage and support structures, on design specifications for the linkage and support structures, and/or on measurements of individual linkages, which may be stored in a non-volatile memory of the slave and/or master control, such as by burning calibration information into a memory of the
25 appropriate structure.

As illustrated in Fig. 11D, much of a servocycle time is used by the controller CE1 to calculate appropriate high-level instructions for the master and slave systems. The results of these calculations are transferred to control processor CTP via yet another DMA interrupt 1014. These high-level commands, typically in the form of
30 desired forces to be applied on the master and slave f_m, f_s in a suitable reference frame such as a Cartesian coordinate system are converted by the control processor CTP to desired motor current signals, which are directed to the appropriate motors by post-processor SCO.

While the pre- and post-processors, timing generator, control processor, and controllers are illustrated schematically in Fig. 11A as separate blocks, it should be understood that some or all of these functional components may be combined, for example, on a single processor board, or that multiple processor boards may be used with the functions of one or more of these components being separated on to separate processors.

As can be understood with reference to Figs. 11A and 11D, while the first controller CE1 is processing the position and other information associated with the first master/slave pair, the pre- and post-processors and control processor are processing and transferring data for use by the second and third controllers CE2, CE3. Hence, the individual controllers have asynchronous input and output times. It should be understood that more than three controllers may be provided for additional master/slave pairs. In the exemplary embodiment illustrated in Fig. 11A, for example, the first and second controllers CE1 and CE2 might be dedicated to left and right hand inputs from the surgeon, while the third controller CE3 may be used to move the endoscope using the left and/or right input device, or any other desired input system.

In the embodiment of Fig. 11A, servo timing generator STG includes a memory storing the master/slave pair assignments 1016. These pair assignments are communicated to the pre- and post-processors SCI, SCO, so that the information transferred to and from the control processor CTP is appropriate for the controller, and so that the commands from the appropriate controller are properly understood and transmitted to the drive system for the appropriate joints. Reallocation of the master/slave pair assignments is transmitted to the timing generator STG from the control processor CTP, and is then communicated from the timing generator to the pre-and post-processors during an intermittent initialization phase, which may also be used to set up appropriate processor time intervals. Alternatively, the time intervals may be fixed.

As should be understood by those of skill in the art, the flexible master/slave pairing controller of Fig. 11A is still a simplification, and an appropriate controller will include a number of additional systems. For example, it is highly beneficial to include fault-checking software to ensure that all encoders or other joint sensors are read during each servocycle, and that the drive systems of each driven joint of the master and slave are written to during each servocycle. If the fault-check is not successfully completed, the system may be shut down. Similarly, the control system may check for changes in pair assignments, for example, during data transfer to and/or from

the camera controller. Similarly, pair assignments may be reviewed during and/or after a tool change, during a left/right tool swap, when handing off tools between two different master controllers, when the system operator requests a transfer, or the like.

It should be noted that the control system of Figs. 11A-11D may

5 accommodate flexible tool mountings on the various manipulators. As described above, the first and second controllers CE1, CE2 may be used to manipulate tools for treating tissue, while the third controller CE3 is dedicated to tool movements using inputs from both master input devices. In general surgical procedures, it may desirable to remove the endoscope or other image capture device from a particular manipulator and instead mount
10 it on a manipulator which was initially used to support a treatment tool. By appropriate commands sent via the control processor CTP to the servo timing generator STG, the pair assignments for the three controllers may be revised to reflect this change without otherwise altering the system operator's control over the system.

During pair re-assignment, appropriate data sets and/or transformations
15 reflecting the kinematics of the master/slave pairs, the relationship of the image capture device with the end effectors, and the like, may be transmitted to the controller. To facilitate swapping the image capture device from one manipulator to another, it may be beneficial to maintain a common manipulator structure throughout the system, so that each manipulator includes drive motors for articulating tools, endoscope image transfer
20 connectors, and the like. Ideally, mounting of a particular tool on a manipulator will automatically transmit signals identifying the tool to the control system, as described in co-pending U.S. Patent Application Serial No. 60/111,719, filed on December 8, 1998, (Attorney Docket No. 17516-003210) entitled "*Surgical Robotic Tools, Data Architecture, and Use.*" This facilitates changing of tools during a surgical procedure.

25 A variety of adaptations of the exemplary control system will be obvious to those of skill in the art. For example, while the exemplary embodiment includes a single master bus and a single slave bus, one or both of these individual busses may be replaced with a plurality of busses, or they may be combined into a single bus. Similarly, while the exemplary servocycle time for an individual control pair is preferably about
30 1,000 msec or less, and ideally about 750 msec or less, the use of higher speed processing equipment may provide servocycle times which are significantly faster.

The master/slave interaction between master control station 200 and cart 300 is generally maintained while the operator O is actively manipulating tissues with surgical instruments associated with his or her left and right hands. During the

course of a surgical procedure, this master/slave interaction will be interrupted and/or modified for a variety of reasons. The following sections describes selected interruptions of the master/slave control interaction, and are useful for understanding how similar interruptions and reconfigurations of the telesurgical robotic network may be provided to enhance the capabilities of the overall robotic system. The exemplary interruptions include “clutching” (repositioning of a master control relative to a slave), repositioning of an endoscope, and a left-right tool swap (in which a tool previously associated with a master control input device in a right hand of a surgeon is instead associated with an input device in a left hand of the surgeon, and *vice versa*.) It should be understood that a variety of additional interruptions may occur, including during removal and replacement of a tool, during manual repositioning of a tool, and the like.

Clutching

In the course of performing a surgical procedure, the surgeon may wish to translationally reposition one or both of the master controls relative to the position or positions of a corresponding end effector or effectors as displayed in the image. The surgeon’s dexterity is generally enhanced by maintaining an ergonomic orientational alignment between the input device and the image of the end effector. The surgeon may reposition the master relative to the end effector by simply interrupting the control loop and re-establishing the control loop in the desired position, but this can leave the end effector in an awkward orientation, so that the surgeon repeatedly opens the control loop to reorient the end effectors for each translational repositioning. Advantageously, the ergonomic rotational alignment between input devices and the images of the end effectors can be preserved after the master control or controls have been repositioned by a modified clutching procedure, which will now be described with reference to Figures 12 and 13.

Referring to Figure 12, a block diagram indicating the repositioning of one of the master controls is indicated generally by reference numeral 450 and will now be described. It will be appreciated that both master controls can be re-positioned simultaneously. However, for ease of description, the repositioning of a single master control will be described. To reposition the master control relative to its associated slave, the surgeon causes the control loop 400 linking master control movement with corresponding slave movement to be interrupted. This is accomplished by activation by the surgeon of a suitable input device, labeled “Depress Master Clutch Button” at 452 in Figure 12. It has been found that such a suitable input device can advantageously be in

the form of a foot pedal as indicated at 208 in Figure 2. It will be appreciated that any suitable input can be provided such as voice control input, a finger button, or the like. It is advantageous to provide an input device which does not require the surgeon to remove his or her hands from the master controls so as to preserve continuity of master control operation. Thus, the input device can be incorporated on the master control device itself instead of having a foot pedal.

Once the input has been activated, e.g., by depressing the foot pedal, the control loop 400 between master and slave is interrupted. The slave is then locked in its position, in other words in the position in which it was at immediately before the foot pedal was depressed.

As can be described with reference to Figure 11, upon depression of the foot pedal, the link 410 in the control system 400 between master and slave is interrupted. The position in joint space of the slave immediately before depression of the foot pedal is recorded in a memory of a slave joint controller indicated at 420 in dashed lines. Should a force then be applied to the slave to cause it to displace to a new joint position, the encoders on the slave relay signals to 414 where a new joint space position for the slave is computed and forwarded to the slave joint controller 420 as indicated by arrow BA9. This new joint space position is compared with the joint space position in the memory, and joint space deviations are determined. From this joint space deviation, torques are computed to return the slave to the joint position as recorded in the memory. These torques are relayed to 414 as indicated by arrow AB9 where corresponding electric motor currents are determined which are forwarded to the slave motors to cause it to restore its joint space position. Thus, the slave position is servo locked.

Referring again to Figure 11, upon depression of the foot pedal at 452, the translational movement of the master is caused to float while its orientation is locked, as indicated at 454 in Figure 12. This step is achieved by a master Cartesian controller with memory as indicated at 422 in Figure 11. The functioning of the master Cartesian controller with memory will now be described with reference to Figure 13.

Upon activation of the foot pedal and repositioning of the master, the joint space position input of the master control as indicated by θ_a is converted from joint space to Cartesian space at 406. From this conversion, a Cartesian space position x_a of the master is obtained. The position in Cartesian space of the master immediately before activation of the foot pedal is recorded in a memory at 424 and is indicated by x_d . The current position x_a of the master as it moves to its new position is compared with the

recorded position x_d at 456 to obtain error signals, which correspond to positional deviations of current master position in Cartesian space when compared with the recorded position x_d in Cartesian space. These deviations or errors are input to a feedback controller at 426 to determine a feedback force to return the master to a position corresponding to the recorded position x_d . The components of the feedback force which corresponds to translational movement are zeroed at 428. Thus, translational feedback force components are zeroed and only orientational force components are forwarded from 428. The orientational force components are then converted to corresponding torques at 408, which are then input to 406 (in Figure 11) to determine currents for feeding to the electric motors on the master to cause its orientation to be urged to remain in a condition corresponding to the orientation determined by x_d . It will be appreciated that the orientation at the position x_d corresponds to the orientation of the slave since the slave continuously tracks the master and the positions were recorded in memory at the same time. Since the translational forces were zeroed, the translational movement of the master is caused to float enabling the surgeon to translate the master to a new, desired position. Such translational floating may alternatively be provided by a variety of other methods. For example, the translational gains of controller 426 may be set to zero. In some embodiments, the translational elements of memory 424 may be continually reset to be equal to the input values x_a , so that the difference between the measured position and the stored position is zero. It should also be understood that despite the zeroing of the translational terms, additional controller functions such as friction compensation, gravity compensation, or the like, may remain unaltered.

Referring again to Figure 12 of the drawings, when the master controls have been moved to their desired position the foot pedal is released. Upon release, the translational deviations relating to the new position of the master control relative to its associated slave is incorporated into 410 to define a new Cartesian space position at which the slave position corresponds to the master position. In particular, the translational derivations may be incorporated in the fixed offsets described above, preferably using the algorithm described herein to avoid inadvertent sudden movements or forces.

Since the orientation of the end effector was held at the same position, and since the master orientation was caused to remain in a corresponding orientation, realignment of the end effector and master is normally not necessary. Re-connection of

master and slave takes place upon release of the foot pedal as indicated at 456. The re-connection will now be described with reference to Figure 19.

Referring to Figure 19, a block diagram illustrating the steps involved in re-connecting the control system 400 between the master and the slave is generally indicated by reference numeral 470.

The first step involving in re-connecting control between the master and the slave, and as indicated at 472, is to determine whether or not the master orientation is sufficiently close to the slave orientation. It will be appreciated that it could happen that during repositioning of the master as described above, the surgeon could be urging the pincher formation on the master away from its orientationally aligned position relative to the slave. Should re-connection of control between master and slave then occur, it could result in reactive motion by the slave resulting from the urging force applied by the surgeon on the pincher formation. This reactive motion by the slave could cause unnecessary damage to organs, or tissue, or the like, at the surgical site and should be avoided. Accordingly, at 472 the orientation of master and slave is compared. If the orientation of the master does not coincide with the orientation of the slave or does not fall within an acceptable orientational deviation, re-connection of control between master and slave will not be enabled. In such a case an appropriate message is typically displayed on the viewer indicating to the surgeon that a required corrective action is required to cause the orientation of the master to be within the acceptable deviational range relative to the orientation of the slave. An example of such a message is one indicating to the surgeon to relax his or her grip on the pincher formation. Simultaneously, the master alignment algorithm may be executed as described hereinbelow with reference to Fig. 18.

When the orientations of master and slave are sufficiently similar, the slave orientation is optionally snapped with the master orientation in Cartesian space as indicated at 474. Once the orientation is snapped, the Jacobian Inverse controller on the slave is enabled as indicated at 476. Thereafter, the Cartesian force reflection commands and gains are downloaded as indicated at 478.

As used herein, the snapping of the slave orientation to the master orientation means that the orientational offsets in bilateral controller 410 are reset to zero, so that the master and slave orientations begin tracking each other. In synchronization with this snapping, the control system 410 is reconfigured to normal bilateral control,

preferably using a Jacobian inverse, as indicated at step 476. The appropriate commands and gains are downloaded as indicated at step 478.

In many embodiments, rather than instantaneously snapping the master to the slave, the orientational offsets in bilateral controller 410 may alternatively be slowly and smoothly reduced to zero, thereby providing a smoother transition between operating modes. This may be effected by, for example, filtering the orientational offset values to zero.

In general, some and/or all transition of control system 400 between operating configurations or modes, including those described with reference to steps 454 and 456 of the master repositioning algorithm of Fig. 12, as well as a variety of similar steps described hereinbelow, may include potentially substantially instantaneous changes in configuration or perimetric values of the control system. For example, interrupting or opening the loop of bilateral controller 410, enabling master Cartesian controller 422, resetting memory 424 or the controller gains in P.I.D. controller 426 might be performed by substantially instantaneously changing the perimetric values and/or configurations. Such instantaneous changes may be fundamentally different than normal master/slave operation, where the computations are continually repeated using fixed perimetric values and operational configurations, with only the sensor readings changing.

Where substantially instantaneous changes in perimetric values and/or configuration are imposed, it is possible that a sudden change in motor currents may result, causing the system to jerk. Such inadvertent instantaneous movements of the system may be transmitted to the surgeon or other system operator, and can be disconcerting and/or reduce the overall feel of control the operator has over the system. Additionally, unexpected rapid movements of a surgical instrument at a surgical site are preferably minimized and/or avoided. Hence, rather than effecting these changes in perimetric values and/or configuration instantaneously, the changes will preferably be timed and executed in a manner so as to avoid significant instantaneous changes in the computed motor currents applied before, during, and after the change in configuration. This smooth change of perimetric values and/or controller configurations may be provided by a "no-jerk" algorithm which will be described with reference to Fig. 19A.

The relevant control system mode transitions typically involve a configuration change, a change in a fixed memory value, or the like. In particular, bilateral controller 410 makes use of fixed offsets in its memory. Controllers 420, 422, and 560 also contain fixed commands in their memories. The no-jerk algorithm, which

generally decreases and/or eliminates rapid inadvertent movement of the master or slave, utilizes known sensor readings, configuration information, and memory values immediately before a control system operating mode transition. By assuming that sensor readings will remain predictable, changing only slightly during the controller mode transition, the no-jerk algorithm computes desired memory reset values by also taking into account the known end values or configuration, and by synchronizing the change in values so as to promote smooth motor current changes during the mode transition. For some uses, the no-jerk algorithm may reduce or eliminate sudden changes in motor torques by using pre-transition (and optionally filtered) motor currents or joint torque values in place of or in combination with the pre-transition sensor configuration and memory values as inputs.

Referring now to Fig. 19A, pre-transition configuration, perimetric values, and memory values are used, together with sampled pre-transition sensor values 702 to compute pre-transition joint torques at step 704. Alternatively, these pre-transition joint torques may be directly observed, optionally with filtering, at step 706. Regardless, post-transition joint torque values are forced to match the pre-transition joint torque values at step 708. Meanwhile, using known post-transition configuration and perimetric values 710, the post-transition effective feedback gains may be determined at step 712. These post-transition effective feedback gains may be inverted and used together with the post-transition joint torques to calculate a desired post-transition error signal at step 714. The post-transition sensor values may be predicted at step 716. These post-transition sensor values may be estimated by assuming that smooth sensor readings will be provided, and knowing the time it takes to effect transition.

The desired post-transition error signal and predicted sensor values may be used to derive a desired post-transition command signal at step 718.

Based on the known post-transition configuration, the post-transition command signal will generally determine the desired memory or offset value through calculations performed at step 720. This post-transition memory or offset value is reset in synchronization with the transition at step 722. Hence, once the desired mode transition is input, information about the configuration of the system before and after the change takes place allows smoothing of the transition.

Repositioning of one of the slaves relative to one of the masters will now be described with reference to Figures 14 and 15. It is to be appreciated that both slaves can be repositioned relative to their associated masters simultaneously. However, for

ease of explanation the repositioning of a single slave relative to its associated master will now be described.

In Figure 14 a block diagram indicating steps involved in repositioning a slave relative to its associated master is generally indicated by reference numeral 500.

5 When it is desired to move the end effector of a slave to a new position, a suitable input is activated to interrupt the control loop 400 between the master and the slave. Such a suitable input can be in the form of a button on the robotic arm as indicated at 480 in Figure 5A. Depressing such a button to interrupt the control loop 400 is indicated by the term "Depress Slave Clutch Button" at 504 in Figure 14. Once the button is depressed,
10 the control between master and slave is interrupted to cause the translational movements of the slave to float while the orientation of the end effector is locked as indicated at 502 in Figure 14.

In general, when movements of one or more joints of a master or slave linkage are allowed to float, the floating joints may optionally still have some forces
15 imposed against the joint by their associated joint-drive systems. More specifically, as described more fully in co-pending U.S. Patent Application Serial No. 09/287,513, the full disclosure of which is incorporated herein by reference, the controller may impose actuation forces on the master and/or slave so as to compensate for gravity, friction, or the like. These compensation forces may be maintained on the floating joint or joints even
20 when the control link for actuating the joint is otherwise open.

The step indicated at 502 will now be described in greater detail with reference in particular to Figure 15, and also with reference to Figure 11. When the button 480 is depressed, the position θ_d of the slave in joint space immediately before depression of the button is recorded in a memory of the slave joint controller 420, and as
25 indicated at 460. As the slave is moved thereafter, its position in joint space indicated by θ_a is compared with θ_d at 462. As θ_a deviates from θ_d error signals corresponding to the positional deviation in joint space is determined at 462 and is passed to 464. At 464 required torques for the electric motors on the slave are determined to cause the slave to return to the θ_d position. The torques thus determined which relate to translational
30 torques of the slaves are zeroed at 466 to permit the slave translational movements to float. The torques corresponding to orientational movement are not zeroed. Thus, any environmental forces on the end effector urging an orientational position change are fed back to the end effector to cause it to retain its orientation. In this way the orientation of the end effector relative to the end of the instrument shaft 104 is locked in position.

Although the orientation of the end effector does not change relative to the end of the shaft, it does change in position in Cartesian space as a result of translational position change. It should be understood that zeroing of the outer joint torques at step 466 may be effected by a variety of methods, including zeroing of the appropriate gains in P.I.D.

5 controller 464, continually updating the appropriate elements in memory 460 so as to compute a zero error signal at comparison 462, or the like.

It should be also be understood that a variety of additional operation configurations may be implemented which allow slave transitional movements to float free of the master control. For example, slave transitional forces may be zeroed in Cartesian space (analogous to the master clutching algorithm described with reference to Figs. 12 and 13). Alternatively, control system 400 and/or bilateral controller 410 may be interrupted only for translational motions, locking the master translational position and allowing the slave to float in transnational position, all while connecting the master orientation to the slave orientation. Once the slave is at the desired position the button is released as indicated at 510 in Figure 14.

When the button is released, the master orientation is re-aligned with the slave orientation as indicated at 512. The re-aligning of the orientation of the master and slave is now described with reference to Figure 18. The steps involved in such re-alignment are generally indicated by reference numeral 550.

At 552 the slave position θ_s in joint space is read. The position θ_s is then converted to a position x_s in Cartesian space at 554 using slave forward kinematics. Thereafter at 556, the desired orientation of the master is set to equal the slave orientation in Cartesian space. Thus x_m , the master orientational position in Cartesian space is set to equal x_s , the slave orientational position in Cartesian space. Thereafter at 558, inverse master kinematics is employed to determine the master joint position θ_m in joint space which corresponds to x_m , the master position in Cartesian space. Finally, the master is then caused to move to θ_m by causing appropriate signals to be sent to the motors on the master as indicated at 560. It will be appreciated that the surgeon will generally release the master to enable it to move into an orientation aligned with the slave orientation.

Referring again to Figure 14, after the re-alignment step at 512, the master is reconnected to the slave as indicated at 513. It will be appreciated that the step 513 is the same as that described above with reference to Figure 19. The master realignment is described in more detail in Application Serial No. 60/116,842.

Endoscope Movement

Referring now to Figures 11, 16, and 17, repositioning of the endoscope to capture a different view of the surgical site will now be described. As the surgeon may wish to view the surgical site from another position, endoscope arm 302 can selectively be caused to vary its position so as to enable the surgical site to be viewed from different positions and angular orientations. The arm 302 includes appropriately positioned electrical motors controllable from the control station 200. The endoscope arm can thus be regarded as a slave and is typically controllable in a control loop similar to that shown in Figure 11. Regarding the endoscope as another slave, cart 300 has three slaves, the robotic arm assemblies 310 and 304, and two masters 210.

To vary the position of the endoscope, the surgeon activates an input at the control station 200. The input can be generated from any appropriate input device, which can include a depressible button, or a voice control system, or the like. Upon such activation, the control loops between master 210 and slaves 310 one of which is indicated in Figure 11, are interrupted and the parts of the control loop on both master sides are operatively linked to a dormant control loop portion similar to that of the slave in Figure 11, but which is arranged to control endoscope arm movement. The surgeon can then change the position of the endoscope to obtain a different view of the surgical site by means of manual inputs on the master controls 210. When the endoscope has been moved to a desired position, control between master and slave is re-established in accordance with the methods described above including automatic assessment of left and right hand allocation between masters and slaves as already discussed.

An exemplary method and system for robotic movement of the endoscope using both of the master controllers is described in more detail in Application Serial No. 60/111,711, filed on December 8, 1998, and entitled "*Image Shifting for a Telerobotic System*," the full disclosure of which is incorporated herein by reference.

At times, such as when the scope is moved to an alternative minimally invasive aperture, or when a scope is removed and replaced, the endoscope may be manually positioned. The steps involved in repositioning the endoscope are indicated by reference numeral 600 in Figure 16. To do this a suitable input device is activated.

The suitable input device is typically in the form of a depressible button on the endoscope arm 302. However other methods such as voice control or the like can be used instead. The button is similar to the button on the arm 312 as described above. The depressing of such a button is indicated at 602 in Figure 16 and is labeled "Depress

camera slave clutch button". Upon activation of the input button the tool slaves and masters are servo locked at the positions they were at immediately before activation of the input button.

When the button is depressed, all the joints on the endoscope arm 302 are caused to float as indicated at 609. This will now be described in greater detail with reference to Figure 17. As soon as the button is depressed, the position of the endoscope in joint space immediately before depression of the button is recorded as indicated by θ_d . When the endoscope arm 302 is then moved to a new desired position, its present position indicated by θ_a in Figure 17 is compared with θ_d at 604 to determine joint positional errors or deviations. These errors are passed to 606. The torques then determined are zeroed at 608 to cause the joints on the endoscope arm to float to enable repositioning.

It will be appreciated that floating the endoscope arm can also be achieved by setting the gains in 606 to zero or continually updating θ_d to watch θ_a as to compute a zero error signal at 604. Similarly one might disable the endoscope arm controller altogether or zero the motor commands.

It will also be appreciated that the endoscope could be freed to move in translation while locked in orientation, analogous to the above-described methods. Furthermore, one could control the orientation to keep the image aligned with horizontal or vertical, that is keep the top of the image facing upward (for example, so that gravity is consistently downward in the image shown to the system operator), while floating translational degrees of freedom. Again this is analogous to methods described above, and can be used to disable and/or float aspects of the endoscope controller in Cartesian space.

When the endoscope arm is brought into the required position the button is released as indicated at 610 in Figure 17. Thereafter the masters are realigned with the slaves as indicated at 612 and as already described with reference to Figure 18. Thereafter at 614 control between master and slave is re-established and as already described with reference to Figure 19.

Though the above algorithms for repositioning masters, slaves and/or the endoscope arm were described in isolation, they can also be executed in parallel, allowing for simultaneous repositioning of any number of system components.

Left-Right Tool Swap

Referring now to Figure 20 of the drawings, in which like reference numerals are used to designate similar parts unless otherwise stated, an image as viewed by the surgeon, and as captured by the endoscope, is generally indicated by reference numeral 800.

During the course of a surgical procedure, the surgeon is often controlling the actions and movements of the end effectors by inputting manual movements and actions on the master controls while viewing the corresponding end effector movements and actions in the image displayed on the viewer. The left hand master control is typically operatively associated with the end effector displayed on the left hand side of the image and the right hand master control is operatively associated with the end effector displayed on the right hand side of the image.

As described above, the surgeon may wish to perform an image shift by moving the viewing end of the endoscope relative to the surgical site to view the surgical site from a different position or angle. It could happen that during the conducting of the surgical procedure, such as subsequent to an image shift, the end effector which was on the left of the displayed image is now on the right, and similarly the end effector which was on the right of the displayed image is now on the left. Furthermore, during the course of, e.g., training, or the like, an operator of the minimally invasive system may wish to operatively associate the two master controls with a single end effector so as to enhance a training procedure of the system. This invention provides a minimally invasive telesurgical system which provides for selectively permitting operative association of any one or more of a plurality of master controls with any one or more of a plurality of end effectors.

The image 800 is schematically indicated in Figure 21 at an enlarged scale. The image 800 indicates the end effectors 102 at the working ends 110 of two surgical instruments similar to the surgical instrument 100 shown in Figure 6. In the image, the portions of the shafts 104 of the surgical instruments extend outwardly from the image on respectively a right hand side and a left hand side of the image. Referring again to Figure 20 of the drawings, the master control device 210 on the right hand side of the surgeon is operatively associated with the slave including the medical instrument defining the shaft extending outwardly toward the right hand side of the image 800. Similarly, the master control device 210 on the left hand side of the surgeon is operatively associated with the slave including the medical instrument defining the shaft extending outwardly

toward the left hand side of the image 800. Accordingly, an anthropomorphic or immersive surgical environment is created at the workstation 200 and the surgeon experiences an atmosphere of directly controlling actions and movements of the end effectors 102.

5 In Figure 21A, the end effectors are shown to be at different positions in the image. However, it is still clear which shaft 104 extends outwardly to the left and right of the image. Accordingly, the same association between the master control devices and the slaves prevails.

10 Referring now to Figure 22 of the drawings, an image shift has taken place. This can happen, for instance, where the surgeon wishes to change the orientation of the surgical site as viewed through the viewer. This can be accomplished by causing the endoscope to displace angularly about its viewing axis. It will be appreciated that the endoscope mounted on the robotic arm 302, as can best be seen in Figure 5, can be caused to displace angularly about its viewing axis from the control station 200.

15 The new image 802 shown in Figure 22 for the sake of example, was brought about by such angular displacement of the endoscope. Accordingly, the image 802 has undergone an angular displacement, as indicated by arrow 804. The shaft of the medical instrument which extended to the right of the image now extends to the left of the image and the shaft of the medical instrument which extended to the left of the image
20 now extends to the right of the image. If the association between masters and slaves which existed immediately before the image shift was to prevail, this would severely impede the surgeon's ability to carry on with the surgical procedure since left hand control would be associated with right hand actions and movements of the end effector as displayed on the viewer, and vice versa.

25 To compensate for such a situation, the minimally invasive surgical system of the invention causes the association between masters and slaves which prevailed immediately before the image shift, to be interrupted and then to be switched or swapped automatically. Once this has taken place, master control on the surgeon's right hand side is associated with the slave which includes the shaft extending outwardly to the right of
30 the new image and the master control on his or her left hand side is associated with the slave defining the medical instrument having the shaft which extends outwardly to the left of the new image. Thus, the anthropomorphic surgical environment is retained at the control station 200.

Referring now to Figure 22B of the drawings, the steps involved in causing the association between a master and a slave to be swapped with the association of another master and slave will now be discussed.

The first step, indicated by reference numeral 900 in Figure 22B of the drawings, is to determine the positions of the remote centers or fulcrums 349 of the slaves relative to a Cartesian space coordinate system having its origin at the viewing end of the endoscope. This step will now be described in greater detail and with reference to Figure 10 of the drawings.

In other words, in the above discussion, and throughout the remainder of the following discussion, the remote centers or fulcrums 349 are considered coincident with the port of entry (as is typical in the preferred embodiment). In other embodiments, however, these points may not coincide (or even exist, for example, when a distal portion or an endoscopic tool is free to pivot above the insertion point, relying on the tendency of the tool to pivot at this point with no remote center imposed) in which case all calculations should be based on the location of the port of entry. It will also be appreciated that the system may determine these port locations from sensor information and pre-existing knowledge of the cart 300, set-up joints, and manipulator arms. Alternatively, the locations could be determined by other sensors or by processing the image 800 directly to observe and extrapolate the pivot points of the displayed tool shafts.

As described above with reference to Figure 10, the positions of each fulcrum are generally determined relative to the Cartesian coordinate system 902, optionally using sensors of the set-up joints. This is indicated at step 911 in the method of Figure 22B after which (at step 913) a determination is made as to whether or not the (X,Y) positions of each fulcrum are sufficiently spaced apart relative to each other to permit the minimally invasive surgical system of the invention to determine a left hand and right hand allocation for the robotic arm assemblies or slaves. This step will now be described in greater detail.

It will be appreciated that the cart or trolley 300 and the robotic arm assemblies 395, 310, and 302 mounted thereon are not mechanically perfect structures. Thus, in computing the (X,Y) coordinates for each fulcrum 349 positional errors can arise due to, e.g., external forces such as gravity, mechanical misalignments, miscalibration and the like. The range of such positional errors which can arise is indicated in Figure 22A. Figure 22A indicates the x-x and y-y axes of the coordinate system 902. The circular part of the shaded area in Figure 22A represents an area corresponding to an error

range or margin resulting from such errors as described above. The parts of the shaded area diverging outwardly along the x-x axis and from the circular part represent regions where the positions of the fulcrums are too close to the x-x axis for an appropriate allocation to be made.

5 To determine whether or not the (X,Y) positions of the fulcrums 349 fall in the shaded area, a midpoint between the (X,Y) positions is transformed onto the x-x and y-y axis as indicated in Figure 22A such that the midpoint coincides with the origin 904. With reference again to Figure 22B of the drawings, should the positions of the fulcrums 349 fall outside the shaded error region, the next step as indicated by reference numeral 10 915 is performed. If not, an alternative method to allocate left and right position is followed as indicated by the step 917, as further described herein below.

The step 915 involves a selection or allocation of a right hand and left hand position to the slaves. Accordingly, the slave defining the fulcrum to the left of the x-x axis in Figure 22A is assigned the left hand position and similarly the slave defining the fulcrum to the right of the x-x axis is assigned the right hand position.

15 When this allocation has been made the step indicated at 919 is performed. The step at 919 involves making a comparison between the allocated left and right hand positions with a previous left and right hand allocation. Should these allocations be the same, the association between masters and slaves stays as it was as indicated at 921.

20 Should the allocation not be the same, the step indicated at 923 is performed.

The step 923 involves requesting a swap between the master and slave associations and will now be described with reference to the block diagram shown in Figure 22C.

25 When performing a swap the control loops between the masters and slaves are temporarily interrupted as indicated at 925. This will now be described with reference to Figure 11 of the drawings. It will be appreciated that the control loop 400 indicates a single control loop which operatively associates a single master with a single slave. The slave side of the loop is indicated below the dashed line in Figure 11 and the master side of the loop is indicated above the dashed line. It will be appreciated that a similar control 30 loop is provided for the other master and slave pair. The control loop of each master and slave pair are interrupted at the bilateral controller in step 925. Upon such interruption the positions of the masters and slaves are locked in position by means of the respective master and slave joint controllers 420, 560 in the case of each master and slave pair.

Referring again to Figure 22C, after interruption of the control loops, the surgeon is then informed that a swap is about to take place at step 927. This step typically involves causing a message to be displayed in the image at the viewer. The message can require that the surgeon provide an input to acknowledge his or her awareness of the swap to take place. Such an input can be generated in any appropriate manner such as upon depression of a button, or by means of voice control, or the like. When such an input is generated, operative association between each master and its new associated slave is then established at step 929. Thus, referring once again to Figure 11 of the drawings, the master side of the control system 400 is linked to the slave side of the other control loop and likewise the master side of the other control loop is linked to the slave side of the control loop 400.

Once the control loops have been connected, each master is moved into alignment with its new associated slave at step 931, as described with reference to Figure 18. Each master can then be connected with its new associated slave at step 933, as described with reference to Figure 19 of the drawings. Once these steps have been performed, operative control between each master and its new slave is fully established as indicated at 914 in Figure 22B.

Returning now to Figure 22B of the drawings, and where the positions of the fulcrums 349 fall within the error margin as indicated in Figure 22A as determined at 911 in Figure 22B, the step indicated at 917 will now be described. At 917, an alternative method of determining positions of the fulcrums is employed. This step involves determining the orientation of the endoscope relative to the cart 300. To determine the orientation of the endoscope relative to the cart the positional sensors are employed to determine whether the viewing end of the endoscope is directed toward or away from the cart. Should the end of the endoscope be directed away from the cart, the right hand slave is automatically allocated a right hand position and the left hand slave is automatically allocated a left hand position at the step 935, this allocation presuming a direction of view as indicated by arrow K in Figure 4. Should the viewing end of the endoscope be directed toward the cart, the left hand slave is allocated a right hand position and the right hand slave is allocated a left hand position at the step 935. Again, allocation presumes a direction of view as indicated by the arrow K in Figure 4. This method is based on the presumption that set up joints, indicated by reference numerals 395 in Figure 9 do not readily cross each other.

It will be appreciated that the endoscope arm 302 can selectively be caused to vary its position so as to enable the surgical site to be viewed from different positions and angular orientations. The arm 302 includes appropriately positioned electrical motors controllable from the control station 200. The endoscope arm can thus be regarded as a
5 slave and is typically controllable in a control loop similar to that shown in Figure 11.

Both masters can optionally be operatively associated with a single slave, e.g., for training purposes. Employing the methods described above will also enable a surgeon selectively to control any one or more of these multiple slave arms with only two masters. Furthermore, two control stations can be operatively associated with a single
10 cart 200. Thus one master of each control station can then be operatively linked to a single slave arm and each other master control with a single other slave arm. This can be advantageous for e.g., training purposes, or the like.

Regarding the endoscope as another slave, the minimally invasive surgical system of the invention accordingly has three slaves, the robotic arm assemblies 310 and
15 304, and two masters 210. As described herein, further slave arms may be incorporated as an optional feature.

It will be appreciated that the allocation steps described above for allocating master and slave association are typically automatically carried out at the commencement of a surgical procedure after the slaves have been brought to initial
20 starting positions at the surgical site. Naturally, in addition, or instead, the allocation steps can be initiated manually when appropriate by activating a suitable input to initialize the allocation steps. The steps are also automatically carried out when either one or both masters are repositioned relative to the slaves, when either one or both slaves are repositioned relative to the associated master or masters and when the endoscope is
25 repositioned, as described earlier in this specification. It is to be appreciated that where an input is required in this specification and where appropriate such an input can be by way of any suitable input, such as buttons, cursor selection foot pedal toggling, voice control or any other suitable form of input.

It will furthermore be appreciated that the determination of master-slave
30 association, which is computed automatically according to Figure 22A and 22B, may be specified manually by way of a suitable input device, such as buttons, a foot pedal, voice control, mouse input, or any other suitable form. If the association is specified manually, only steps 911 and 916 need be performed to execute the association.

In a system with more than two masters or more than two robotic arms with associated instruments, master-slave association will preferably be entered manually. This can be accomplished by interrupting the current association to allow the master to translate freely as described above with reference to Figures 12 and 13, then using the floating master as a mouse-like pointing device to highlight and/or select the image of one of the slaves. To complete the process, the master is locked and the new association activated using steps 919 and 923. Any slaves that are not part of an existing association are locked in joint space using controller 420. The slave location at the time of disassociation is stored in memory in 420, and compared against the sensor signals to provide appropriate feedback torques.

Similarly, in a system with more masters than slaves, only masters selected by appropriate input devices are associated with slaves, while the remainder are locked using a controller such as controller 560.

Robotic Network

Referring now to Figures 1, 23A and 23B, many of the above steps may be used to selectively associate any of a plurality of tools with any of a plurality of input devices. Operator O may initiate a tool selection subroutine 910 by actuating a tool selector input, such as by depressing foot activated button 208a of workstation 200 (illustrated in Figure 2). Assuming operator O is initially manipulating tools A and B with input devices 210L and 210R using his or her left and right hands LH and RH, respectively, tool selector procedure 910 will be described with reference to a change of association so that input device 210L is instead associated with a tool C, here comprising a tissue stabilizer 120.

Once the tool selector subroutine is activated, the operator will generally select the desired tools to be actively driven by the robotic system. The surgeon here intends to maintain control over Tool B, but wishes to reposition stabilizer 120. Optionally, operator O will select between the left and right input devices for association with the newly selected tool. Alternatively, the processor may determine the appropriate left/right association based on factors more fully described in co-pending U.S. Patent Application Serial No. 60/116,891, filed on January 22, 1999, and entitled "*Dynamic Association Of Master And Slave In A Minimally Invasive Telesurgical System*," (Attorney Docket No. 17516-004700) the full disclosure of which is incorporated herein by reference.

Optionally, operator O may select the desired tools for use by sequentially depressing selector input 208a, with the processor sequentially indicating selection of, for example, Tools A and B, then B and C, then A and C, and the like. Controller station 200 may indicate which tools are selected on display 800, audibly, or the like. For example, the image of the selected tools viewable by the surgeon may be colored green to designate active manipulation status, and/or the deselected tools may be colored red. Preferably, any deselected tools (for example, Tool A) will be maintained in a fixed position per step 914. The tools may be held in position using a brake system and/or by providing appropriate signals to the drive motors of the tool and arm actuation system to inhibit movement of the tool. The tool fixation step 914 will preferably be initiated before a master input device is decoupled from the tool, so that no tool moves absent an instruction from an associated master. Tool fixation may occur simultaneously with tool selection. The selected master may be allowed to float, step 916, during and/or after tool fixation and tool selection.

Once the selected master has been allowed to float, the master may be moved into alignment with the selected tool as illustrated in Figure 23A, as was described above with reference to Figure 18. Often, this will occur while the surgeon keeps a hand on the input device, so that the drive motors of the master should move the master at a moderate pace and with a moderate force to avoid injury to the surgeon. Master input device 210L may then be coupled to tool C (stabilizer 120 in our example) while tool A is held in a fixed position. This allows the operator to reposition stabilizer 120 against an alternative portion of coronary artery CA. The tool selection process may then be repeated to re-associate the masters with tools A and B while tool C remains fixed. This allows the surgeon to control repositioning of stabilizer 120 without significantly interrupting anastomosis of the coronary artery CA with the internal mammary artery IMA.

A number of alternative specific procedures may be used to implement the method outlined in Figure 23B. Optionally, the interface may allow the operator to manually move the input devices into apparent alignment with the desired tools while the tool selector button is depressed. In Figure 23A, the surgeon might manually move master 210L from alignment with tool B into approximate alignment with tool C. The processor could then determine the tools to be driven based on the position of the input devices when the button is released, thereby allowing the operator to “grab” the tools of

interest. Some or all of the tools (Tools A, B, and C) may optionally be maintained in a fixed configuration when the operator is moving the master controllers to grab the tools.

Allowing an operator to sequentially control more than two robotic tools using the operator's two hands can provide significant advantages. For example, referring again to Figure 1, by allowing operator O the ability to select in real time and control any one or two tools 100 of cart 300 and auxiliary cart 300A, the surgeon will often be able to act as his or her own assistant.

In addition to allowing the operator to safely reposition a stabilizer 100 against a coronary artery and the underlying beating heart during beating heart coronary artery bypass grafting, a variety of alternative procedures would also be facilitated by such capabilities. As another example, in the procedure of gall bladder removal (cholecystectomy), the surgeon will generally want to first to provide exposure of the organ (retraction) to expose the area of interest. This generally involves guiding a retractor tool (mounted, for example, to a first manipulator arm) to expose an area of interest. The area of interest may be exposed for viewing through an endoscope mounted, for example, to a second manipulator arm. The surgeon might thereafter want to use two hands to direct tools in dissecting tissue covering the cystic duct and artery while the retractor remains stationary. One of the two tools (which may be mounted on third and fourth manipulator arms) can be used to stretch the tissue (traction or grasping) while the other tool is used to cut tissue (sharp dissection) to uncover the vessel and duct structures. Hence, the ability to selectively control four manipulators from a single console allows the surgeon to control the manipulation, retraction/stabilization, and viewing angle of the procedure, without having to verbally instruct an assistant.

At any time during the dissection, the surgeon could have the capability of adjusting the exposed area of the cystic duct by again selectively associating a master input device in his or her left or right hand with the retractor. Once the desired change in exposure is obtained by repositioning the retractor, the surgeon can deselect the retraction tool, and then select and move the endoscope to a more appropriate viewing angle for work on the newly exposed tissue. Thereafter, the surgeon can again select the grasping and cutting tools to manipulate the tissues using both hands.

The ability to control four or more surgical arms also gives the surgeon the capability of selecting from among alternative tools based on tool function and/or anatomical constraints. For example, tools A, B, and C may all have end effectors comprising universal graspers. If the surgeon is afforded a better approach to tissue

dissection by using the manipulator arms associated with tools A and B in certain parts of a two-handed dissection procedure, but would prefer to use tools B and C for alternative portions of the two-handed dissection procedure, the operator is free to switch back and forth between tools A and C using tool selection subroutine 910. Similarly, if a
5 cauterizing electrode blade is desired intermittently during a dissection, the operator may switch back and forth between tools A and C to dissect, and then cauterize, and then dissect, etc., without having to wait for an assistant to repeatedly swap tools.

Advantageously, providing a “redundant” manipulator may reduce the need for a laparoscopic surgical assistant who might otherwise be called on to perform
10 intermittent functions by manually manipulating a tool handle extending from an aperture adjacent the manipulator arms. This can help avoid interference between manual tools, personnel, and the moving manipulator arms, and may have economic advantages by limiting the number of highly skilled personnel involved in a robotic surgical procedure. The procedure time may also be decreased by avoiding the time generally taken for a lead
15 surgeon to verbally direct an assistant.

Tool Hand-Off

Many of the steps described above will also be used when “handing-off” control of a tool between two masters in a tool hand-off subroutine 920, as illustrated in Figure 24. Tool hand-off is again initiated by actuating an appropriate input device, such
20 as by depressing foot pedal 208b shown in Figure 2.

The tool to be transferred will typically be designated, again using any of a variety of designation input methods or devices. The transfer tool may be coupled to any master input device or devices, including an input device of master control station 200, assistant control station 200A, or auxiliary input 12 of auxiliary cart 300A (as illustrated
25 in Figure 1). Optionally, the input device which will assume control of the designated tool is also selected in designation step 922, although selection between left and right masters may again be left to the processor, if desired.

Once the tool and master are designated, the hand-off tool (and any tool previously associated with the designated master) is fixed, and the designated master is
30 allowed to float. The master is then aligned and connected with the tool as described above.

Camera Switch and Right Access Robotic CABG

The following pertains to an exemplary robotic surgery procedure that may be performed with the foregoing apparatuses and methods. Referring now to Figures 1, 25A, and 25B, a single complex minimally invasive surgery will often involve

5 interactions with tissues that are best viewed and directed from different viewing angles. For example, in performing a Coronary Artery Bypass Grafting (CABG) procedure on patient P, a portion of the internal mammary artery IMA will be harvested from along the internal surface of the abdominal wall. The internal mammary artery IMA can be used to supply blood to coronary artery CA downstream of an occlusion, often using an end-to-
10 side anastomosis coupling the harvested end of the IMA to an incision in the side of the occluded coronary artery. To provide appropriate images to Operator O at master control station 200, the operator may sequentially select images provided by either a first scope 306a or a second scope 306b for showing on display 800 of the workstation. The camera switch procedure can be understood through a description of an exemplary CABG
15 procedure in which different camera views may be used. Two scopes are shown in Fig. 25A for illustrative purposes only. If only one image is desired, however, the procedure need not employ two endoscopes but instead need only use one together with various instruments for actually performing the procedure.

As seen in Fig. 1 and 25A, it may generally be beneficial to access heart H
20 primarily through a pattern of apertures 930 disposed along a right side of patient P. Although the heart is primarily disposed in the left side of the chest cavity, approaching the heart from the left side of the chest as is typically done for MIS heart surgery may limit the amount of working volume available adjacent the target coronary tissues. This lack of working volume can complicate thoracoscopic robotic procedures, as the lack of
25 space can make it difficult to obtain a panoramic view of the heart surrounding the tissues targeted for treatment, to quickly insert and remove tools, and to retract the heart appropriately for multi-vessel cases.

By inserting the elongate shafts of instruments 100 through the right side of the patient, the apertures will be further away from the target anatomy, including the
30 left internal mammary artery (LIMA) and heart H. This approach can allow the camera to be separated from the target tissues by a greater distance, such as when a panorama or “big-picture” view is desired, while the resolution of robotic movement maintains the surgeon’s dexterity when the scope and tools extend across the chest to the heart tissues for close-up views and work. The right-side approach may also increase the speed with

which tools can be changed, as the additional separation between the aperture and the heart helps to ensure that the heart is not in the way when delivering tools to harvest the IMA. When performing multi-vessel cases with the right-side approach, the heart can also be repeatedly retracted and repositioned so as to sequentially expose target regions of the heart to the significant working volume available. Hence, different coronary vessels may selectively be present to operator O for bypassing.

Advantageously, the right-side approach also facilitates dissection of the left internal mammary artery (LIMA) using a medial to lateral approach. This dissection approach can provide a well-defined dissection plane, can increase the ease with which branches can be seen, and may provide a view that is more familiar to surgeons accustomed to traditional CABG performed via a median sternotomy.

As can be seen most clearly in Figures 1 and 25B, cart 300 supports first and second tools 100a, 100b for manipulating tissues (more may be used but are not shown) and first scope 306a, while auxiliary cart 300A supports second scope 306b (and/or other manipulator tools, not shown). The arms of cart 300 preferably extend over the patient from the patient's left side, and the instruments extend through aperture pattern 930. The instrument shafts are generally angled to extend radially outwardly from aperture pattern 930 in a "spoked wheel" arrangement to minimize interference between the manipulators. The exemplary arrangement has scopes 306a, 306b extending through apertures defining the top and bottom (anterior and posterior relative to the patient) positions of aperture pattern 930, while the manipulation tool shafts define left and right (inferior and superior relative to the patient) positions. Second scope 306b may be positioned through a lower, more dorsal aperture than shown, with the patient optionally being supported on a table having an edge RE which is recessed adjacent aperture pattern 930 to avoid interference between the auxiliary cart manipulator and the table.

A robotic right-side approach CABG procedure might be outlined as follows:

1. General anesthesia is initiated.
2. Patient is prepped in a basic supine position with a small roll under the patient's scapula and back.
3. Patient is draped so that drapes start at about the posterior axillary line.

LIMA Dissection:

4. Camera aperture for second scope 306b is cut in an appropriate innerspace (usually the 5th intercostal space) on approximately the anterior axillary line. The first camera port may be positioned more medially for directing anastomosis, and the like. If provided or desired, the camera aperture for the first scope 306a is cut in an appropriate innerspace (usually the 4th or 5th intercostal space) slightly posterior to the midclavicular line. Obviously, port placement for the endoscopic tools as well as other portions of this procedure may vary depending upon the anatomy of the particular patient in question.

5. Initiate insufflation at approximately 10 mm Hg.

6. Manipulation tool apertures are cut as appropriate (usually in the 3rd and 6th or 7th intercostal spaces for manipulation instruments 100a, 100b) a few centimeters medial to the anterior auxiliary line. Additional tool ports are placed as desired.

7. Robotic instruments 100a, 100b, 306a, 306b introduced through apertures and robotic telesurgical control system is initiated.

8. LIMA harvesting is initiated by locating midline to establish the beginning of dissection. Harvesting may be viewed and directed using second scope 306b.

9. LIMA is located by moving laterally using blunt dissection and cautery as desired.

10. Left pleura need not be entered, although insufflation can help keep left lung out of the way.

RIMA Dissection (if desired)

11. The right internal mammary artery (RIMA) may be harvested using steps similar to 1-10 above, optionally through apertures disposed along the left side of the patient's chest.

Pericardiotomy

12. Incision may be made at surgeon's discretion. Preferably, any incision will be high up on the pericardium, so that an attachment of the mediastinum to the chest forms a tent to enhance exposure of the heart.

IMA Preparation

13. IMA(s) may be prepared per surgeon's preference, typically while still attached to the chest.

Aorta Exposure

14. Aorta is exposed by extending the pericardiotomy cephalad as desired. The pulmonary artery and any other adhesions may be dissected off so that the aorta can be clamped for cardio-pulmonary bypass and/or proximal grafts. As can be understood with reference to the description above of Figure 23A, cardioplegia may be avoided by using a manual or robotic cardiac tissue stabilizer mounted to, for example, auxiliary cart 300A during the anastomosis.

Coronary Artery Exposure

15. Target coronary artery or arteries can be exposed to working volume by retracting and repositioning heart as desired, and standard techniques may be used to expose and incise the exposed coronary arteries.

Anastomosis

16. Anastomosis may be performed using needle-grasping tools 100a, 100b while viewing display 800, as illustrated in Figure 23A.

15 Suturing and exposure of the aorta and coronary artery or arteries may at least in part be performed while viewing the more anterior-to-posterior field of view provided from first scope 306a, as may portions of all other steps throughout the CABG procedure. When the surgeon desires to change views between first and second image capture devices, the surgeon may initiate the view change procedure by activating a view change input device, possibly in the form of yet another foot switch. The tissue manipulation tools will be briefly fixed in position, and the display will shift between the image capture devices--for example, from the image provided from first scope 306a, to the image provided from second scope 306b.

20 Optionally, the processor can reconfigure the coordinate transformations between the masters and the end effectors when changing between two different image capture devices to re-establish an at least substantially connected relationship. This transformation modification is similar to the process described above for a change in scope position, but will generally also accommodate the differences in support structure of the image capture devices. In other words, for example, the master and/or slave kinematics 408, 412 (see Figure 11) may be redefined to maintain a correlation between a direction of movement of the input device 210 and a direction of movement of an image of the end effector 102 as shown in display 202 when viewing the end effector from a different scope. Similarly, when moving second scope 306b (supported by auxiliary cart

300A) as a slave after a scope change from scope 306a (which is supported by cart 300), the slave kinematics 412, slave input/output 414, and slave manipulator geometry 416 may all be different, so that the control logic between the master and slave may be revised as appropriate.

5 More easily implemented approaches might allow the operator O to switch views between scopes 306a and 306b without major software revisions. Using software developed to perform telesurgery with a single master control station 200 coupled to a single three arm cart 300 (see Figure 1), switching the view to scope 306b from scope 306a might be accomplished while maintaining the substantially connected relationship
10 by “fooling” the processor of the master control station into believing that it is still viewing the surgery through scope 306a. More accurately, the processor may be fed signals which indicate that the middle set-up joint 395 and/or manipulator arm 302 of cart 300 are supporting scope 306a at the actual orientation of scope 306b. This may be accomplished by decoupling the position sensing circuitry of the middle set-up joint
15 and/or manipulator of cart 300 from the processor, and instead coupling an alternative circuit that transmits the desired signals. The alternative “fooling” circuit may optionally be in the form of a sensor system of an alternative set-up joint and/or manipulator 302, which might be manually configured to hold a scope at the orientation of scope 306b relative to cart 300, but which need not actually support anything. The image may then
20 be taken from scope 306b supported by auxiliary cart 300A, while the slave position signals x_s (See Figure (11)) are taken from the alternative set-up joint. As described above, so long as the orientation of the end effectors relative to the scope are accurately known, the system can easily accommodate positional corrections (such as by the translational clutching procedure described above).

25 Alternative telesurgical networks are schematically illustrated in Figures 26 and 27. As mentioned above, an operator O and an Assistant A3 may cooperate to perform an operation by passing control of instruments between input devices, and/or by each manipulating their own instrument or instruments during at least a portion of the surgical procedure. Referring, now to Figure 26, during at least a portion
30 of a surgical procedure, for example, cart 305 is controlled by Operator O and supports an endoscope and two surgical instruments. Simultaneously, for example, cart 308 might have a stabilizer and two other surgical instruments, or an instrument and another endoscope A3. The surgeon or operator O and assistant A3 cooperate to perform a stabilized beating heart CABG procedure by, for example, passing a needle or other

object back and forth between the surgical instruments of carts 305, 308 during suturing, or by having the instruments of cart 308 holding the tissue of the two vessels being anastomosed while the two instruments of cart 305 are used to perform the actual suturing. Such cooperation heretofore has been difficult because of the volumetric space
5 required for human hands to operate. Since robotic surgical end effectors require much less space in which to operate, such intimate cooperation during a delicate surgical procedure in a confined surgical space is now possible. Optionally, control of the tools may be transferred or shared during an alternative portion of the procedure.

Referring now to both Figures 26 and 27, cooperation between multiple
10 systems is also possible. The choice of how many masters and how many corresponding slaves to enable on a cooperating surgical system is somewhat arbitrary. Within the scope of the present invention, one may construct a single telesurgical system's architecture to handle five or six manipulators (e.g., two masters and three or four slaves) or ten or twelve manipulators (e.g., four masters and six or eight manipulators), although
15 any number is possible. For a system having multiple master controls, the system may be arranged so that two operators can operate the same surgical system at the same time by controlling different slave manipulators and swapping manipulators as previously described.

Alternatively, it may be desirable to have a somewhat modular telesurgical
20 system that is capable both of conducting one particular surgical operation with only one operator and, for example, five or six manipulators, and which is also capable of coupling to another modular system having five or six manipulators to perform a second surgical procedure in cooperation with a second operator driving the second system. For such modular systems, five or six manipulator arms are preferably supported by the
25 architecture, although any number may be incorporated into each system. One advantage of the modular system over a single, larger system is that when decoupled, the modular systems may be used for two separate simultaneous operations at two different locations, such as in adjacent operating rooms, whereas such might be quite difficult with a single complex telesurgical system.

As can be understood with reference to Figure 26, a simple manner of
30 having two surgical systems, each having an operator, to cooperate during a surgical procedure is to have a single image capture device, such as an endoscope, produce the image for both operators. The image can be shared with both displays by using a simple image splitter. If immersive display is desired, the two systems might additionally share a

common point of reference, such as the distal tip of the endoscope, from which to calculate all positional movements of the slave manipulators, all as previously described in U.S. Appl. No. 60/128,160. With the exception of the imaging system, each control station might be independent of the other, and might be operatively coupled

5 independently to its associated tissue manipulation tools. Under such a simple cooperative arrangement, no swapping of slave manipulators from one system to another would be provided, and each operator would have control over only the particular slave manipulators attached directly to his system. However, the two operators would be able to pass certain objects back and forth between manipulators, such as a needle during an

10 anastomosis procedure. Such cooperation may increase the speed of such procedures once the operators establish a rhythm of cooperation. Such an arrangement scenario may, for example, be used to conduct a typical CABG procedure, such that one operator would control the endoscope and two tissue manipulators, and the other operator would control two or three manipulators to aid in harvesting the IMA and suturing the arterial blood

15 source to the blocked artery downstream of the particular blocked artery in question. Another example where this might be useful would be during beating heart surgery, such that the second operator could control a stabilizer tool in addition to two other manipulators and could control the stabilizer while the first operator performed an anastomosis.

20 One complication of simple cooperative arrangements is that if the first operator desired to move the image capture device, the movement might alter the image of the surgical field sufficiently that the second operator would no longer be able to view his slave manipulators. Thus, some cooperation between the operators, such as audible communications, might be employed before such a maneuver.

25 A slightly more complicated arrangement of surgical manipulators on two systems within the scope of the present invention, occurs when operators are provided with the ability to "swap" control of manipulator arms. For example, the first operator is able to procure control over a manipulator arm that is directly connected to the second operator's system. Such an arrangement is depicted in Figure 26.

30 With the ability to operatively hook multiple telesurgical systems together, an arrangement akin to a surgical production line can be envisioned. For example, a preferred embodiment of the present invention is shown in Figure 27. Therein, a single master surgeon O occupies a central master control operating room. Satellite operating rooms (ORs) 952, 954 and 956 are each operatively connected to the central master

console via switching assembly 958, which is selectively controlled by Operator O.

While operating on a first patient P1 in OR 956, the patients in ORs 954 and 952 are being prepared by assistants A2 and A3, respectively. During the procedure on patient

P1, patient P3 becomes fully prepared for surgery, and A3 begins the surgery on the

5 master control console dedicated to OR 952 by controlling manipulator assembly 964.

After concluding the operation in OR 956, Operator O checks with A3 by inquiring over an audio communications network between the ORs whether A3 requires assistance. OR

950 might additionally have a bank of video monitors showing the level of activity in

each of the Ors, thereby permitting the master surgeon to determine when it would be best

10 to begin to participate in the various ongoing surgeries, or to hand control off to others to

continue or complete some of the surgeries.

Returning to the example, if A3 requests assistance, O selects OR 952 via

switching assembly 958, selects a cooperative surgery set-up on an OR-dedicated

switching assembly 960, and begins to control manipulator assembly 962. After

15 completion of the most difficult part of the surgery in OR 952, O switches over to OR

954, where patient P2 is now ready for surgery.

The preceding description is a mere example of the possibilities offered by the cooperative coupling of masters and slaves and various telesurgical systems and

networks. Other arrangements will be apparent to one of skill in the art reading this

20 disclosure. For example, multiple master control rooms can be imagined in which several master surgeons pass various patients back and forth depending on the particular part of a

procedure being performed. The advantages of performing surgery in this manner are

myriad. For example, the master surgeon O does not have to scrub in and out of every

procedure. Further, the master surgeon may become extremely specialized in performing

25 part of a surgical procedure, e.g., harvesting an IMA, by performing just that part of a

procedure over and over on many more patients than he otherwise would be able to treat.

Thus, particular surgical procedures having distinct portions might be performed much

more quickly by having multiple surgeons, with each surgeon each performing one part of

the procedure and then moving onto another procedure, without scrubbing between

30 procedures. Moreover, if one or more patients (for whatever reason) would benefit by

having a surgeon actually be present, an alternative surgeon (different from the master

surgeon) may be on call to one or more operating rooms, ready to jump in and address the

patient's needs in person, while the master surgeon moves on treat another patient. Due

to increased specialization, further advances in the quality of medical care may be achieved.

In addition to enabling cooperative surgery between two or more surgeons, operatively hooking two or more operator control stations together in a telesurgical
5 networking system also may be useful for surgical training. A first useful feature for training students or surgeons how to perform surgical procedures would take advantage of a “playback” system for the student to learn from a previous operation. For example, while performing a surgical procedure of interest, a surgeon would record all of the video information and all of the data concerning manipulation of the master controls on a
10 tangible machine readable media. Appropriate recording media are known in the art, and include videocassette or Digital Video Disk (DVD) for the video images and/or control data, and Compact Disk (CD), e.g., for the servo data representing the various movements of the master controls.

If two separate media are used to record the images and the servo data,
15 then some method of synchronizing the two would be desirable during feedback, to ensure that the master control movements substantially mirror the movements of the slave manipulators in the video image. A crude but workable method of synchronization might include a simple time stamp and a watch. Preferably, both video images and servo data would be recorded simultaneously on the same recording medium, so that playback
20 would be automatically synchronized.

During playback of the operation, a student could place his hands on the master controls and “experience” the surgery, without actually performing any surgical manipulations, by having his hands guided by the master controls through the motions of the slave manipulators shown on the video display. Such playback might be useful, for
25 example, in teaching a student repetitive motions, such as during suturing. In such a situation, the student would experience over and over how the masters might be moved to move the slaves in such a way as to tie sutures, and thus hopefully would learn how better to drive the telesurgical system before having to perform an operation.

The principles behind this playback feature can be built upon by using a
30 live hand of a second operator instead of simple data playback. For example, two master control consoles may be connected together in such a way that both masters are assigned to a single set of surgical instruments. The master controls at the subordinate console would follow or map the movements of the masters at the primary console, but would preferably have no ability to control any of the instruments or to influence the masters at

the primary console. Thus, the student seated at the subordinate console again could “experience” a live surgery by viewing the same image as the surgeon and experiencing how the master controls are moved to achieve desired manipulation of the slaves.

An advanced version of this training configuration includes operatively coupling two master consoles into the same set of surgical instruments. Whereas in the simpler version, one console was subordinate to the other at all times, this advanced version permits both master controls to control motion of the manipulators, although only one could control movement at any one time. For example, if the student were learning to drive the system during a real surgical procedure, the instructor at the second console could view the surgery and follow the master movements in a subordinate role. However, if the instructor desired to wrest control from the student, e.g., when the instructor detected that the student was about to make a mistake, the instructor would be able to override the student operator by taking control over the surgical manipulators being controlled by the student operator. The ability to so interact would be useful for a surgeon supervising a student or second surgeon learning a particular operation. Since the masters on the instructor’s console were following the surgery as if he were performing it, wresting control is a simple matter of clutching into the surgery and overriding the control information from the student console. Once the instructor surgeon had addressed the issue, either by showing the student how to perform a certain part of the surgical procedure or by performing it himself, the instructor could clutch out of the operation and permit the student to continue.

An alternative to this “on-off” clutching – whereby the instructor surgeon is either subordinate to the student or in command – would be a variable clutch arrangement. For example, again the instructor is subordinate to the student’s performance of a procedure, and has his masters follow the movement of the student’s master controls. When the instructor desires to participate in the procedure, but does not desire to wrest all control from the student, the instructor could begin to exert some control over the procedure by partially clutching and guiding the student through a certain step. If the partial control was insufficient to achieve the instructor’s desired result, the instructor could then completely clutch in and demonstrate the desired move, as above. Variable clutching could be achieved by adjusting an input device, such as a dial or a foot pedal having a number of discrete settings corresponding to the percentage of control desired by the instructor. When the instructor desires some control, he or she could operate the input device to achieve a setting of, for example, 50 percent control, in order

to begin to guide the student's movements. Software could be used to calculate the movements of the end effectors based on the desired proportionate influence of the instructor's movements over the student's. In the case of 50 % control, for example, the software would average the movements of the two sets of master controls and then move the end effectors accordingly, producing resistance to the student's desired movement, thereby causing the student to realize his error. As the surgeon desires more control, he or she could ratchet the input device to a higher percentage of control, finally taking complete control as desired.

Other examples of hooking multiple telesurgical control stations together for training purposes will be apparent to one of skill in the art upon reading this disclosure. Although these training scenarios are described by referring to real surgery, either recorded or live, the same scenarios could be performed in a virtual surgical environment, in which, instead of manipulating the tissue of a patient (human or animal) cadaver, or model, the slave manipulators could be immersed, in a virtual sense, in simulation software. The software would then create a simulated virtual surgical operation in which the instructor and/or student could practice without the need for a live patient or an expensive model or cadaver.

While the present invention has been described in some detail, by way of example and for clarity of understanding, a variety of changes, adaptation, and modifications will be obvious to those of skill in the art. For example and without limiting effect, robotic systems having more than four manipulators and/or more than two scopes may be provided. The manipulator arms can all be mounted to a single support base, or might be arranged with two arms on each of two separate support bases. Hence, the scope of the present invention is limited solely by the appended claims.